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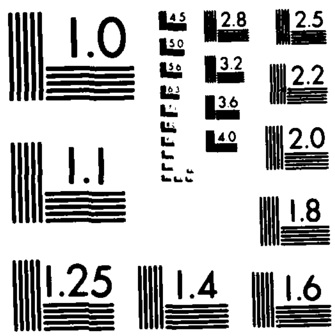

NPS67-84-019

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

MEASUREMENT OF TURBOFAN/TURBOJET THRUST
FROM TAILPIPE STATIC PRESSURE

by

Todd Williams Givens

and

John A. LeMoine

December 1984

Thesis Advisor: O. Biblarz

Approved for public release; distribution unlimited

Prepared for:
Naval Air Engineering Center
Lakehurst, NJ 08733

NAVAL POSTGRADUATE SCHOOL
Monterey, California

Commodore R.H. Shumaker
Superintendent

David A. Schrady
Provost

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The most accurate method for measuring turbojet/turbofan thrust is mechanical. A more practical method is often desired, however, since a mechanical device is costly and non-portable. An investigation was conducted to determine whether inferring thrust indirectly from pressure provides sufficient accuracy to justify its use as an alternate technique for determining uninstalled thrust.

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TF41 engine data were provided by the Naval Air Rework Facility at Jacksonville, Florida. The data consisted of a variety of engine parameters which had been recorded during routine post-maintenance performance tests plus an additional set of tailpipe static pressure readings that had been obtained from a "slave" tailpipe used for this project.

It was decided to approach the data evaluation empirically. The engine data were combined and an ensemble plot of tailpipe static pressure versus thrust was produced for analysis. A curve fitting technique was then employed to determine how well the parameter correlated with thrust.

The results were tested statistically and found to be reasonable. Correlation between thrust and tailpipe static pressure was excellent.

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1. Please attach the paragraph below to the report, "Measurement of Turbofan/Turbojet Thrust from Tailpipe Static Pressure".

PAGE 9

The solid lines shown in Figures 5-8 and B1-B3 represent the regression curve. On the other hand, the solid lines indicated in Figures 11-18 are not regression curves but have been drawn according to TF41-manufacturer's specifications. These lines are to be interpreted as boundaries of regions of acceptability. Consult Reference 3 for further details.

Oscar Biblarz

OSCAR BIBLARZ

Measurement Of Turbofan/Turbojet Thrust From Tailpipe Static Pressure

by

Todd Williams Givens
Commander, United States Navy
B.S.A.E., Georgia Institute of Technology, 1967

and

John A. LeMoine
Major, United States Marine Corps
B.S.G., Villanova University, 1973

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requirements for the degree of

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December 1984

Authors: Todd Williams Givens
Todd Williams Givens

John A. LeMoine
John A. LeMoine

Approved by: Oscar Biblarz
O. Biblarz, Thesis Advisor

T.H. Gawain
T.H. Gawain, Co-Advisor

M. F. Platzer
M.F. Platzer, Chairman
Department of Aeronautics

J. N. Dyer
John N. Dyer,
Dean of Science and Engineering

ABSTRACT

The most accurate method for measuring turbojet/turbofan thrust is mechanical. A more practical method is often desired, however, since a mechanical device is costly and non-portable. An investigation was conducted to determine whether inferring thrust indirectly from pressure provides sufficient accuracy to justify its use as an alternate technique for determining uninstalled thrust.

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This task was initiated by a contract with the Naval Air Engineering Center (NAEC) under the direction of Dr. A. Elshinnawy.

LIST OF SYMBOLS/ABBREVIATIONS

S/N	Serial Number
ps6	Tailpipe Static Pressure
ps6c	ps6 Corrected for Standard Conditions
m	Mass Flow Rate
ρ	Density
γ	Ratio of Specific Heats
p or p	Static Pressure
r	Sample Correlation Coefficient
rho	Population Correlation Coefficient
pt5.1	Stagnation Pressure @ Station 5:1 (See Figure D2)
WFC	Corrected Fuel Flow
WAIC	Corrected Airflow
NLC	Corrected Speed, Low Press. Spool
NHC	Corrected Speed, High Press. Spool

I. INTRODUCTION

The accurate measurement of uninstalled thrust for a turbojet or turbofan aircraft engine is best accomplished mechanically in a properly calibrated, well-instrumented, environmentally controlled test cell. This technique suffers, however, from a rather high degree of sophistication (which translates directly to high cost) and a lack of portability. Further, if a large number of engines are to be measured, the extensive time involved in transporting, hook-up, etc. can profoundly impact maintenance turn-around-time and, therefore, operational readiness.

Thrust can also be measured indirectly; that is, by measuring other parameters and inferring the thrust from those measurements. Intuitively, the accuracy of this technique will depend on the accuracy of the measurements and on the ability of a mathematical model to correctly represent the thrust. Tests have been conducted by the National Aeronautics and Space Administration (NASA) and the United States Air Force (USAF) to verify the accuracy of in-flight thrust measurement techniques, with promising results. Of particular interest are the results of tests of a "simplified gross thrust calculation technique" conducted by NASA using the F100 augmented turbofan engine [Refs. 1, 2]. These tests concluded that a model based on empirically

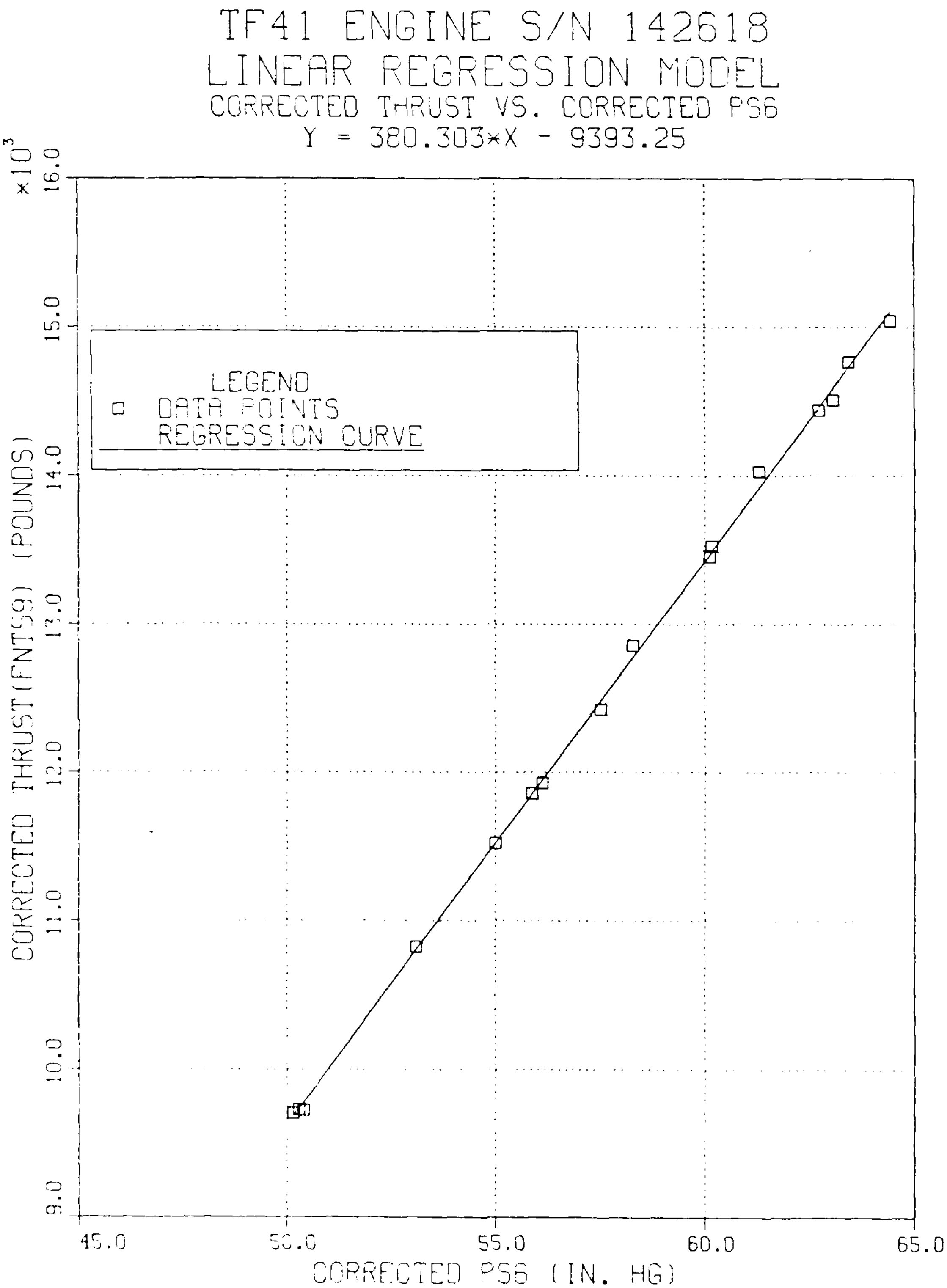


Figure 8 Engine S/N 142618 Line

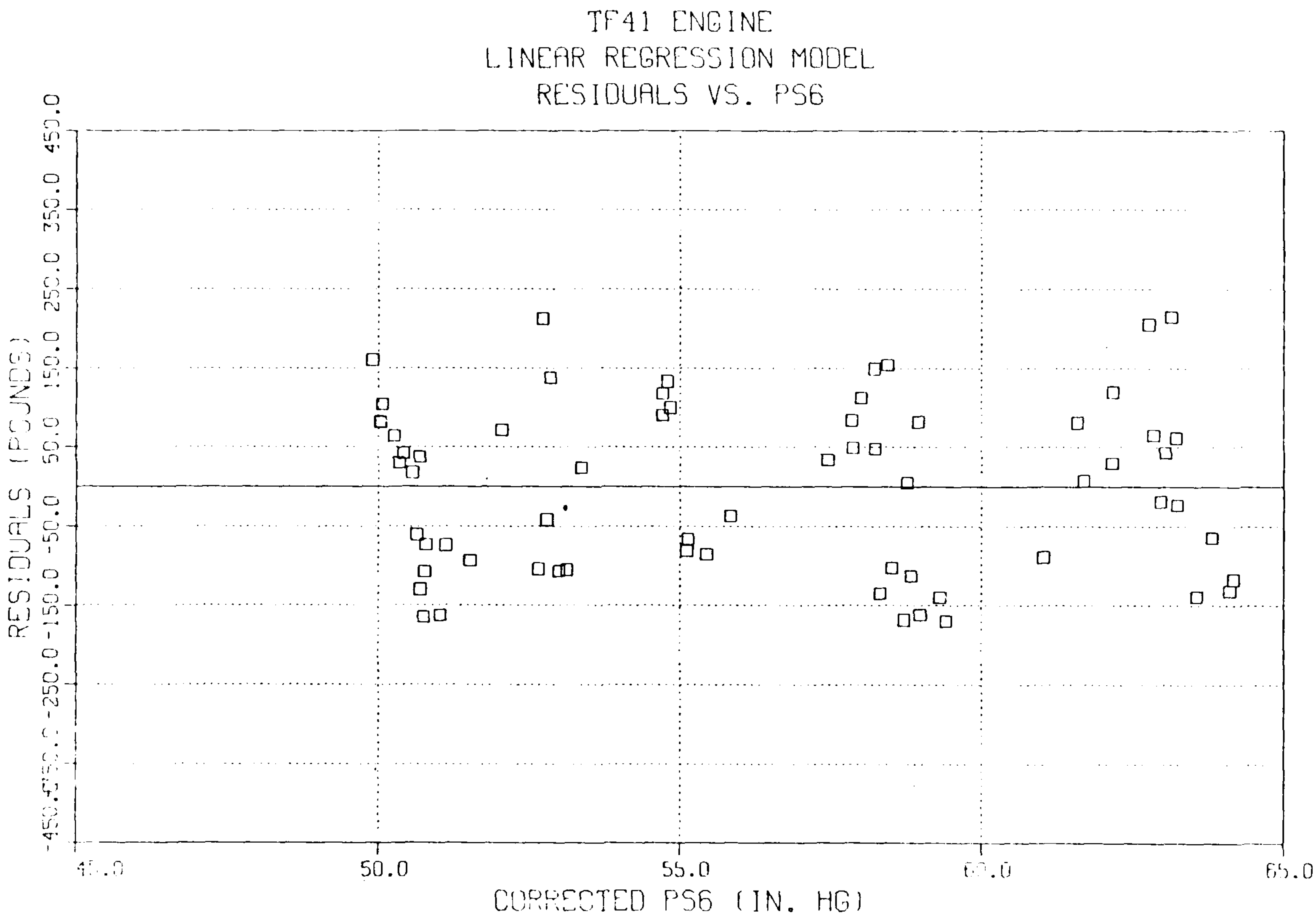


Figure 7 Residuals vs. ps6 (Revised)

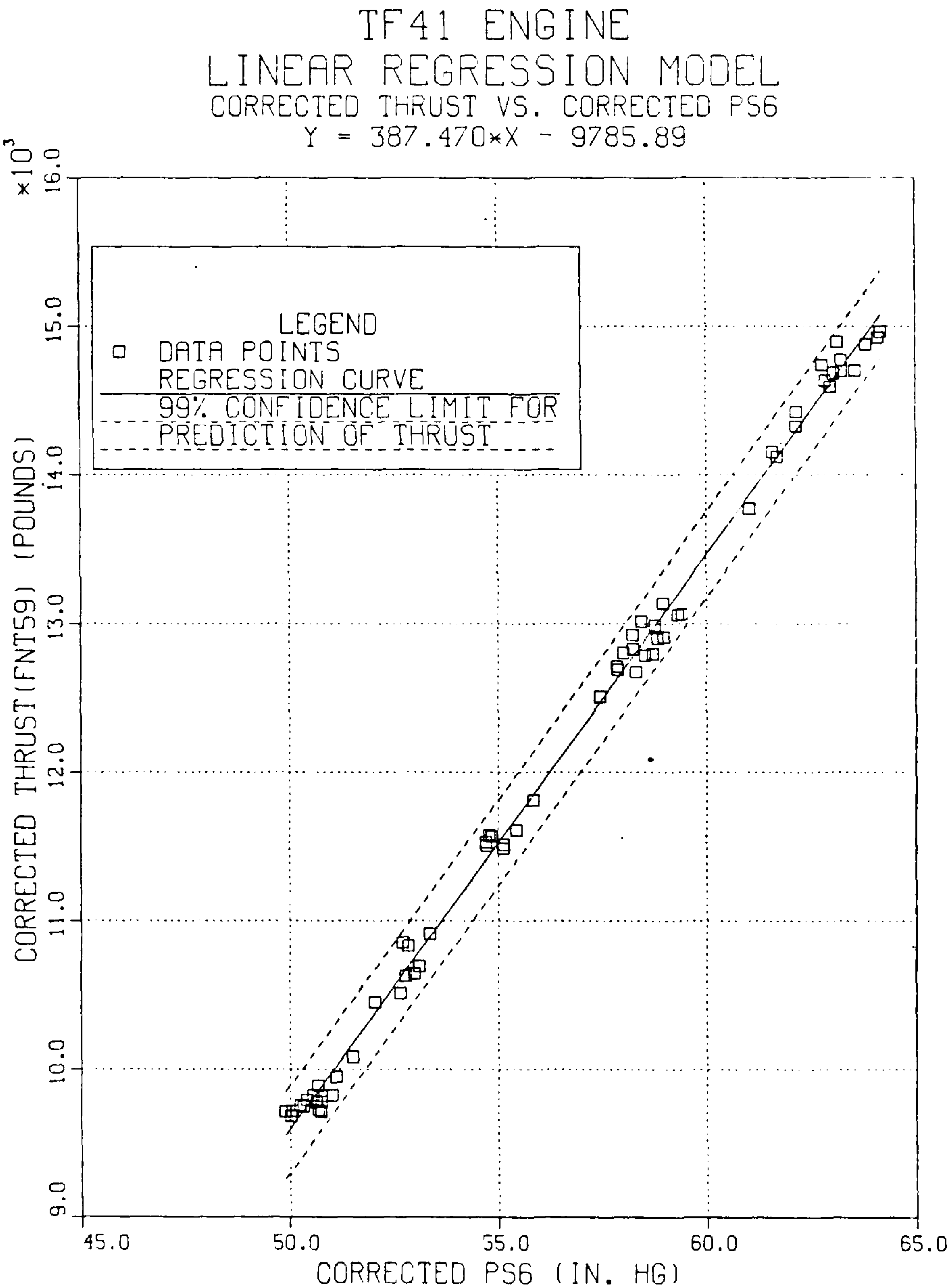


Figure 6 Thrust vs. ps6 (Revised, 99% Conf.)

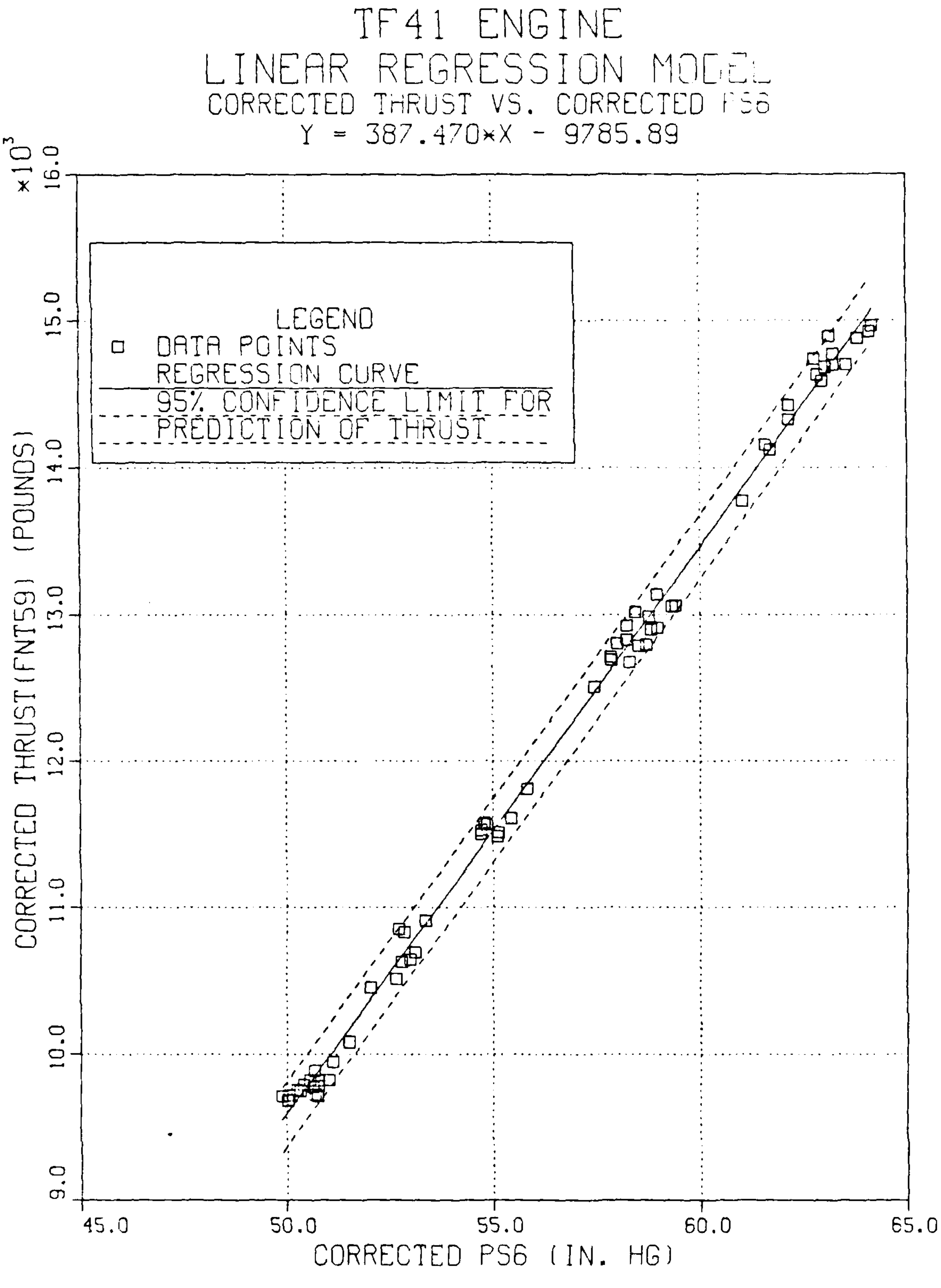


Figure 5 Thrust vs. ps6 (Revised)

rework. As an indication that the model presented in Figure 5 or 6 could be effectively used, these parameters were also plotted against predicted thrust for comparison. These plots are included as Figures 9 through 18.

TABLE 2

ENGINE S/N	REGRESSION EQUATION	r
141481	FNT(59)=386.4*PS6C-9623.9	0.9994
141525	FNT(59)=386.7*PS6C-9680.9	0.9999
142634	FNT(59)=391.3*PS6C-9845.3	0.9999
141954	FNT(59)=390.0*PS6C-9823.2	0.9996
141427	FNT(59)=387.5*PS6C-9912.8	0.9998
141972	FNT(59)=385.9*PS6C-9814.8	0.9999
141440	FNT(59)=394.9*PS6C-10245.6	0.9998
142633	FNT(59)=385.2*PS6C-9635.2	0.9998
141257	FNT(59)=389.1*PS6C-9966.9	0.9997

A revised regression model, excluding the two outliers, is presented in Figures 5 and 6. A corresponding plot of residuals is presented in Figure 7.

Additional data were provided for a "correlation engine" which had been used to verify calibration of the test cell. These data were not included in the above because a pressure rake had been placed in the inlet area which, presumably, would influence the pressure readings within the engine. A separate analysis was conducted on those data and the results are presented in Figure 8. Note that, again, a strong correlation exists, although the regression equation is somewhat altered.

Reference 3 requires that the NARF plot other engine parameters against thrust to verify engine performance after

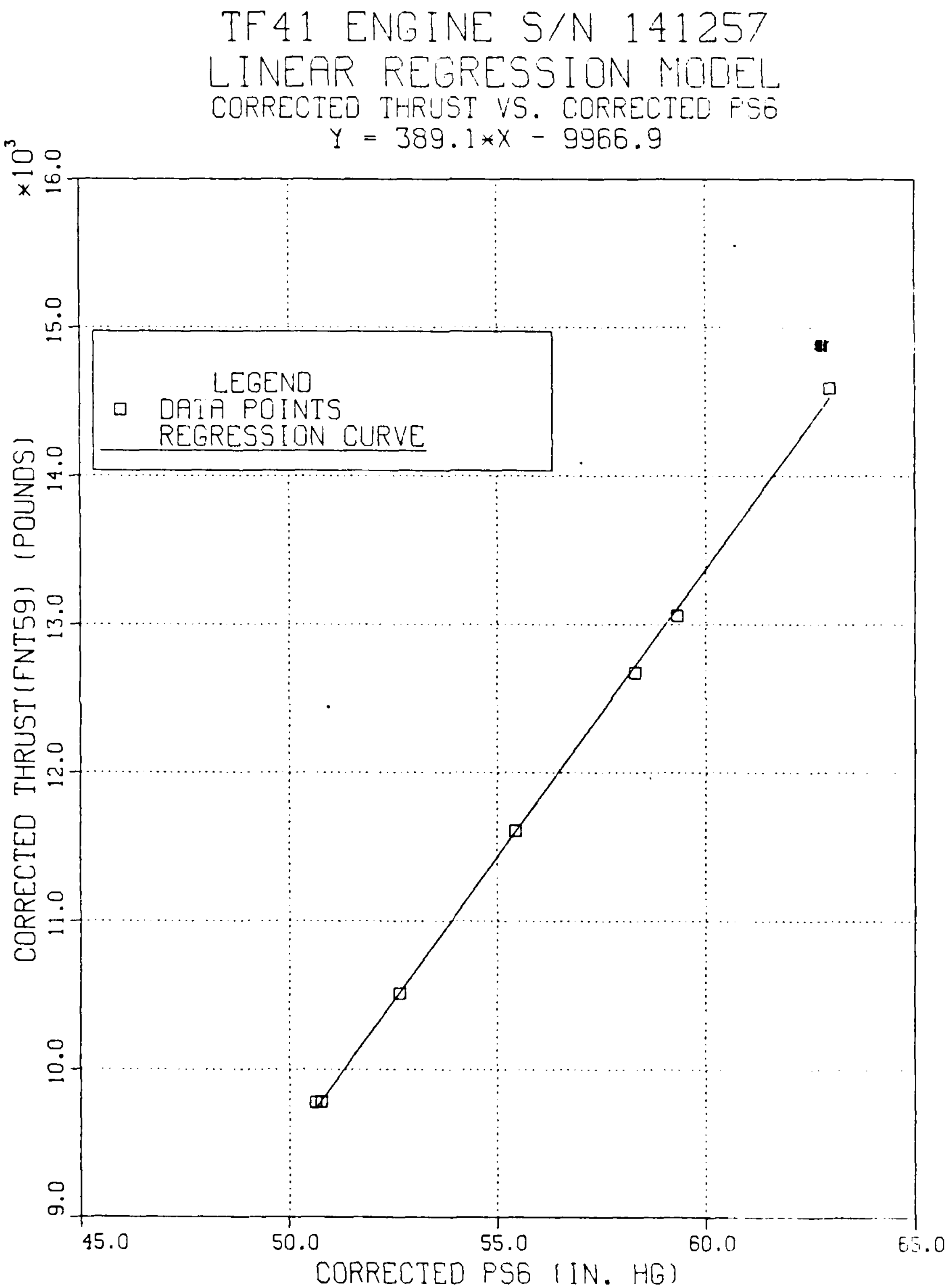


Figure 4 Engine S/N 141257 Line

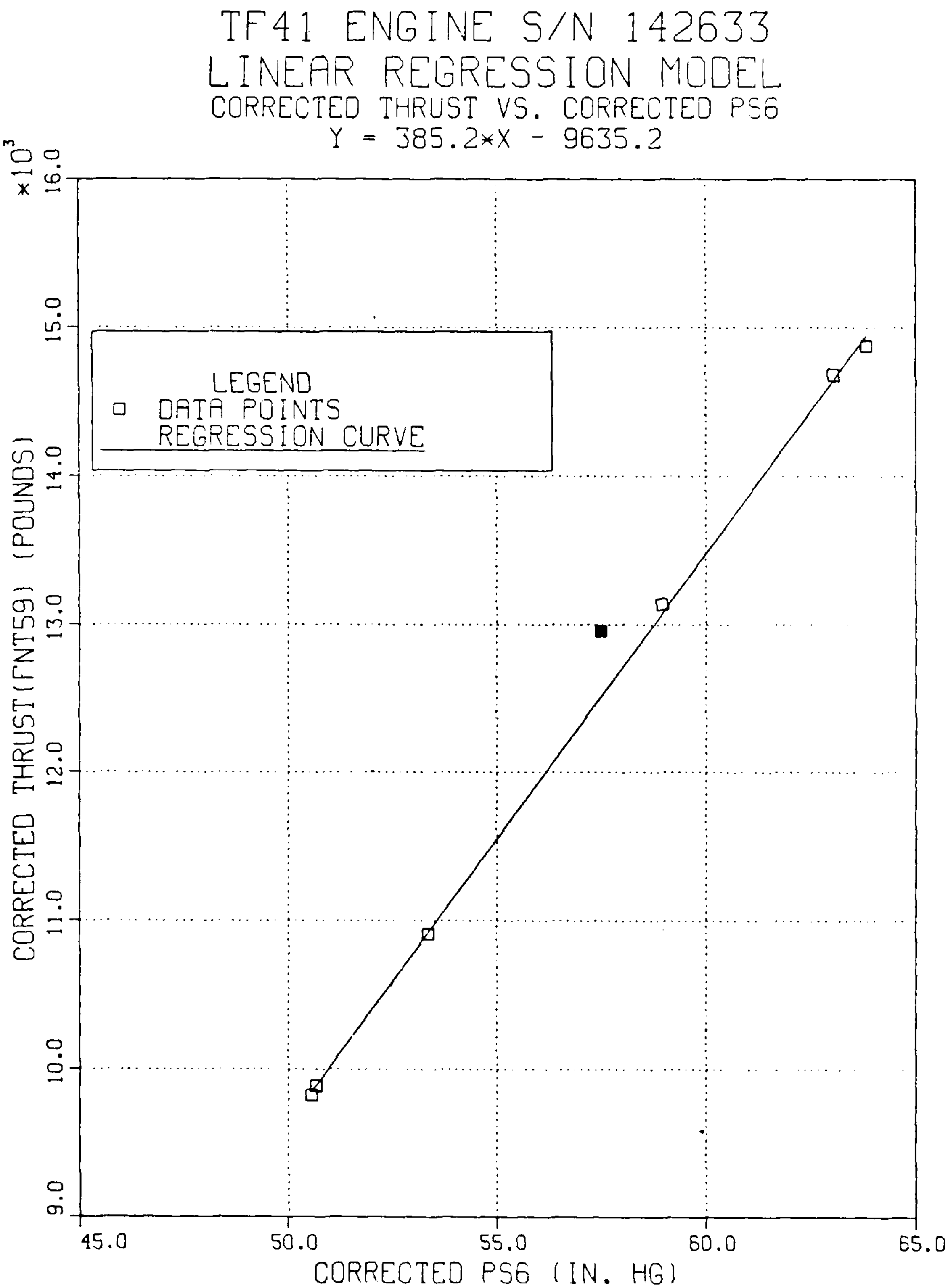


Figure 3 Engine S/N 142633 Line

TABLE 1

ENGINE S/N	REGRESSION EQUATION	r
141481	FNT(59)=386.4*PS6C-9623.9	0.9994
141525	FNT(59)=386.7*PS6C-9680.9	0.9999
142634	FNT(59)=391.3*PS6C-9843.3	0.9999
141954	FNT(59)=390.0*PS6C-9823.2	0.9996
141427	FNT(59)=387.5*PS6C-9912.8	0.9998
141972	FNT(59)=385.9*PS6C-9814.8	0.9999
141440	FNT(59)=394.9*PS6C-10245.6	0.9998
142633	FNT(59)=386.8*PS6C-9661.8	0.9967
141257	FNT(59)=404.1*PS6C-10766.5	0.9977

Plots of these two engines are shown in Figures 3 and 4 respectively. Note that the regression equation plotted in each case excludes the two points that are highlighted. Upon their exclusion, these two engines are brought in line with the rest, as shown in Table 2. These two points are the same outliers as noted in the residuals plot, Figure 2.

Since the data had been recorded by hand and transcribed onto a hand written data sheet, it seemed plausible to assume that an error or two could have been made, and since exclusion of these two points resulted in "improved behavior" of their respective engines, these two outliers were also excluded from the overall analysis.

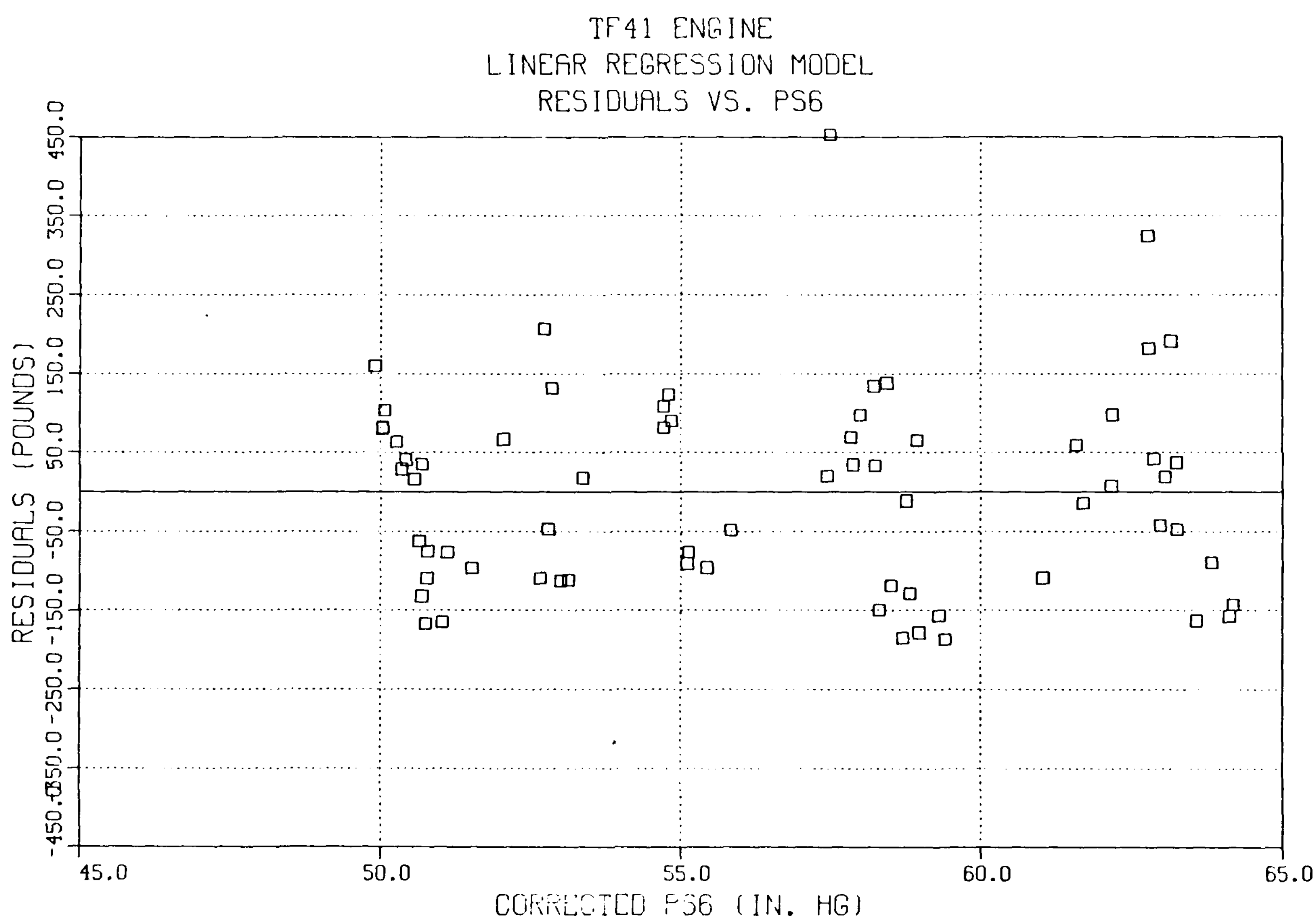


Figure 2 Residuals vs. ps6

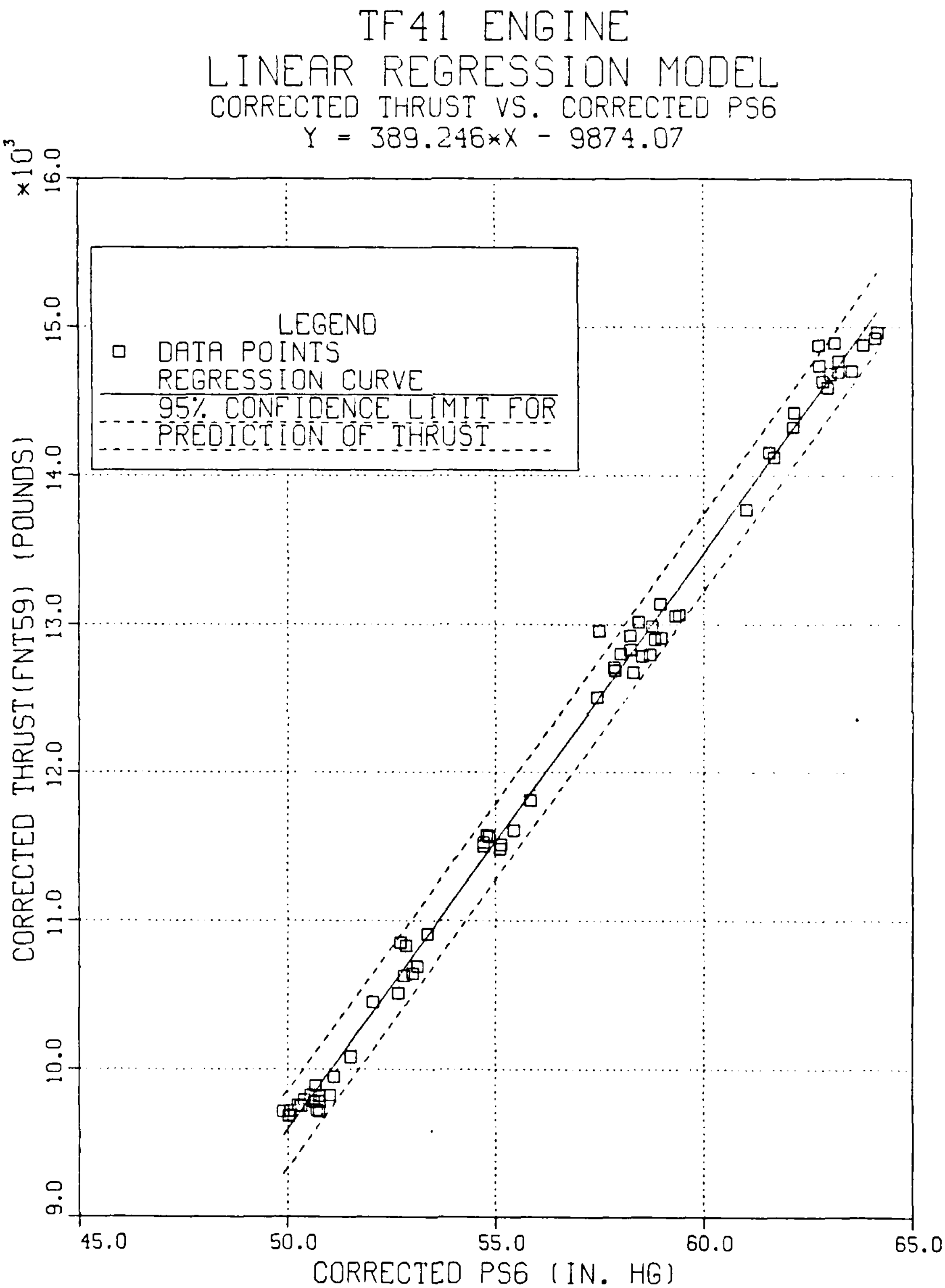


Figure 1 Thrust vs. ps6

III. RESULTS

The model resulting from the initial regression analysis (see Appendix B) is shown in Figure 1 and the plot of residuals is shown in Figure 2. The correlation coefficient resulting from this analysis is excellent, but further investigation was indicated in order to evaluate two features of the results.

First, two outliers are readily apparent from examination of Figure 2 and an explanation was sought for such radical departures from an otherwise well-behaved distribution. Secondly, the data in Figure 1 are an ensemble of data points from nine different engines. The behavior of individual engines was considered to be of interest in order to gain at least a qualitative feel for the repeatability of the data.

To accomplish this further analysis, each engine was evaluated separately and the results compared. Although the number of data points was necessarily reduced (to an average of eight), the results, as presented in Table 1, show strong correlation for each engine and good agreement among engines, with two exceptions.

Engines S/N 142633 and 141257 differ slightly from the others either in the correlation coefficient (142633) or in the regression equation itself (141257).

II. NATURE OF THE PROBLEM

Several analytical techniques for measuring and/or calculating thrust that have been utilized in past efforts were evaluated. For the purposes of this project, however, they all suffer from the same deficiency. All require the measurement of more parameters than desired. Further, judging from past efforts, the models would require considerable empirical "correcting" before acceptable accuracy could be achieved. As an example, utilization of "a very complex gas generator method (GGM)" [Ref. 1] for evaluating the thrust of the F100 engine required measuring ten parameters (including fan speed, IGV position, area, pressures, temperatures and airflows); and "calibration" was still required.

It was decided, therefore, to approach the data evaluation empirically at the outset. Since it can be shown (by a first order analysis) that thrust varies directly with tailpipe static pressure (see Appendix A), the engine data were combined and an ensemble plot of tailpipe static pressure (ps6) versus thrust was produced for analysis. A curve fitting technique was then employed to determine how well the parameter correlated with thrust and an error analysis was conducted in order to evaluate the uncertainty associated with the regression (see Appendix B).

corrected, ideal, one-dimensional thermodynamic relationships could predict in-flight thrust with an uncertainty of less than three percent, using only four pressure measurements.

Our project sought to investigate the feasibility of employing a relatively unsophisticated, and therefore low cost, indirect method for measuring uninstalled thrust with acceptable accuracy. Since aircraft inlet flow distortion and most other flow interference effects are absent from the uninstalled thrust measurement problem, it seemed reasonable to assume that measuring uninstalled thrust indirectly could be accomplished more accurately than measuring in-flight thrust, and/or fewer measured parameters would be needed. To simplify the problem somewhat, a turbofan engine without augmentation was chosen as the test candidate (TF41).

Performance tests of a randomly selected group of TF41 engines were conducted at the Naval Air Rework Facility (NARF), Jacksonville, Florida in conjunction with routine post-maintenance evaluations. These engines were evaluated in accordance with the requirements of reference 3 with a modified tailpipe to provide tailpipe static pressure data in addition to the data routinely produced (Appendix D). All data were then forwarded to the Naval Postgraduate School for analysis.

TF41 ENGINE

PT5.1 VS. THRUST

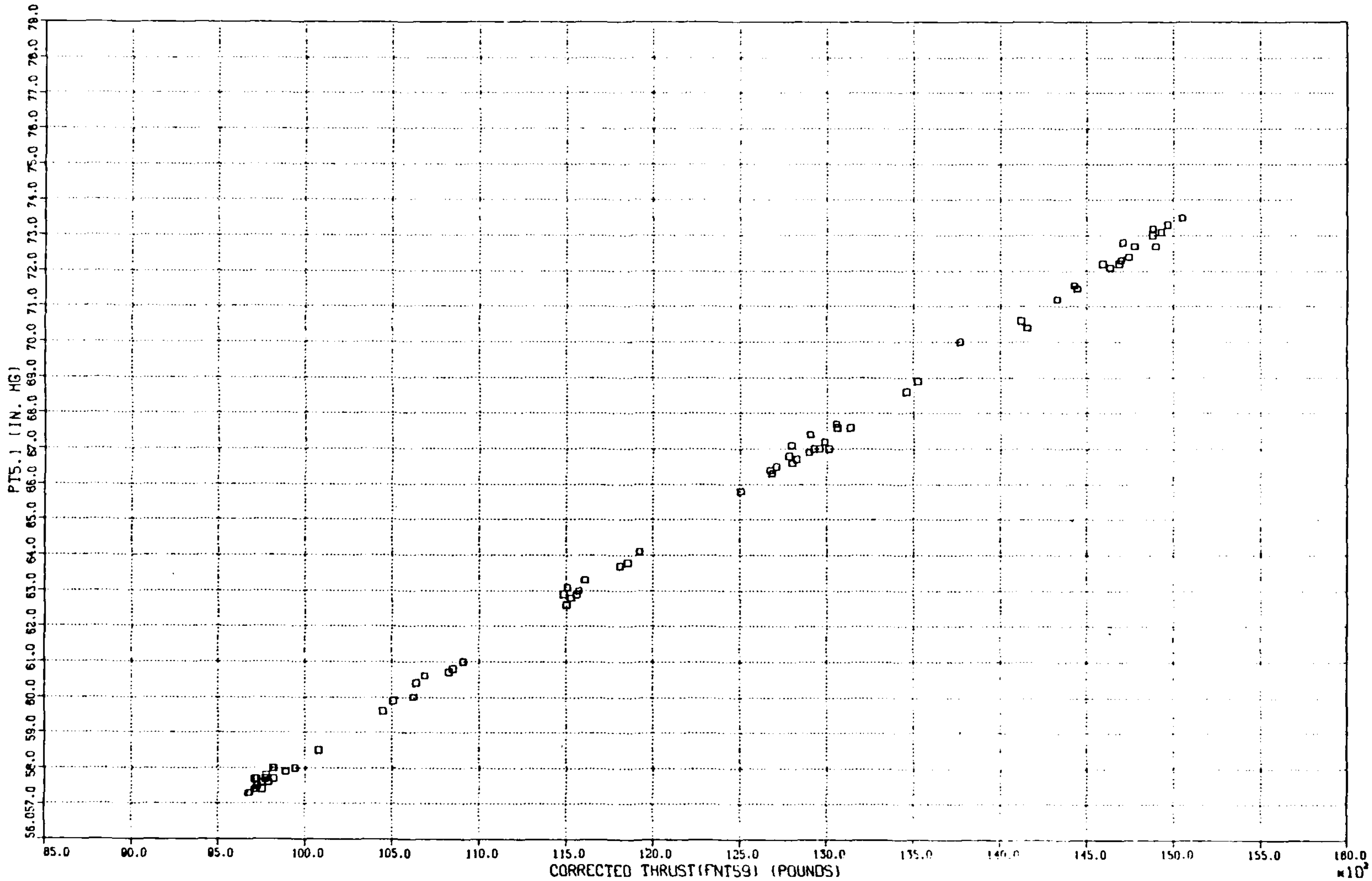


Figure 9 pt5.1 vs. Thrust

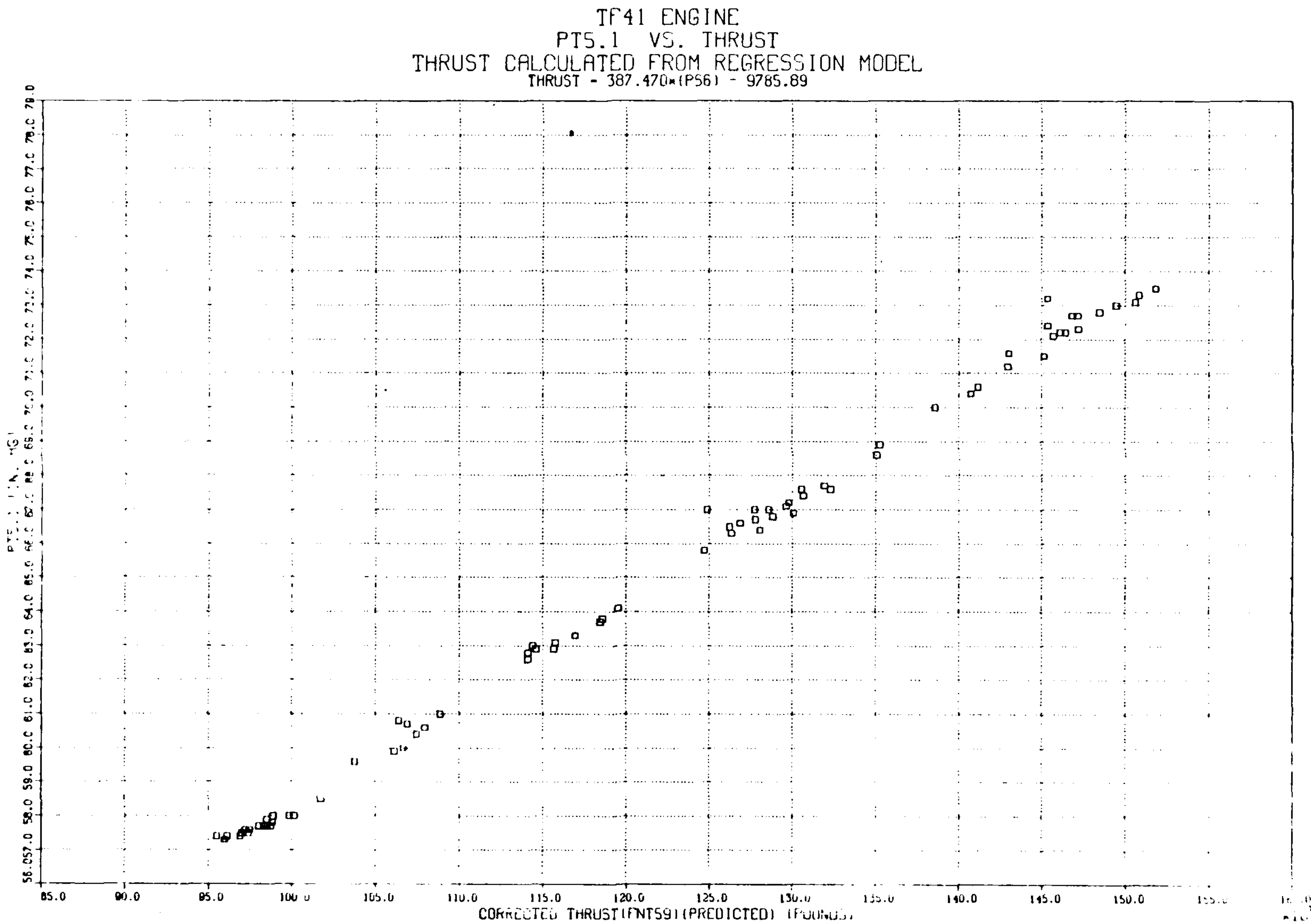


Figure 10 pt5.1 vs. Predicted Thrust

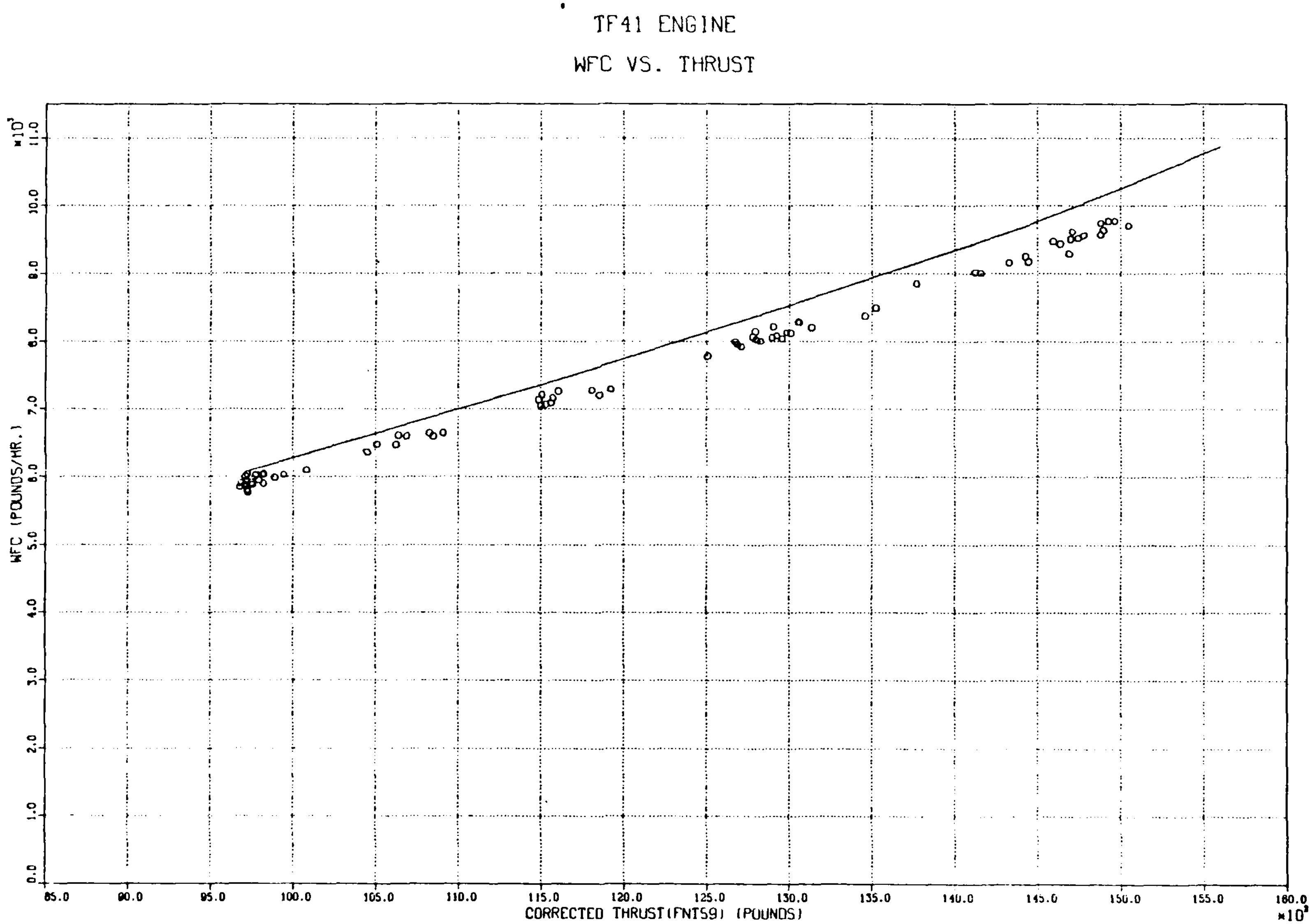


Figure 11 WFC vs. Thrust

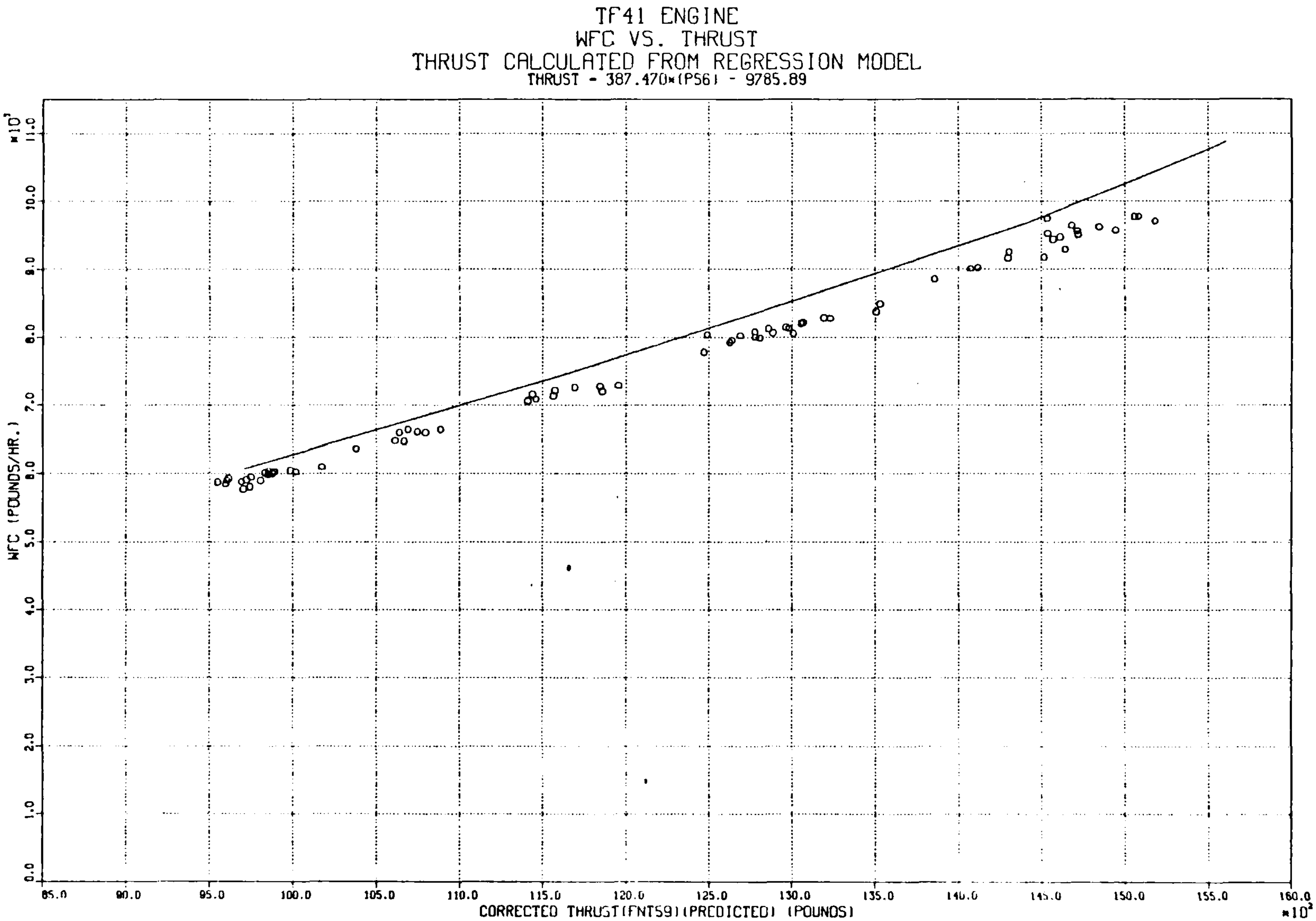


Figure 12 WFC vs. Predicted Thrust

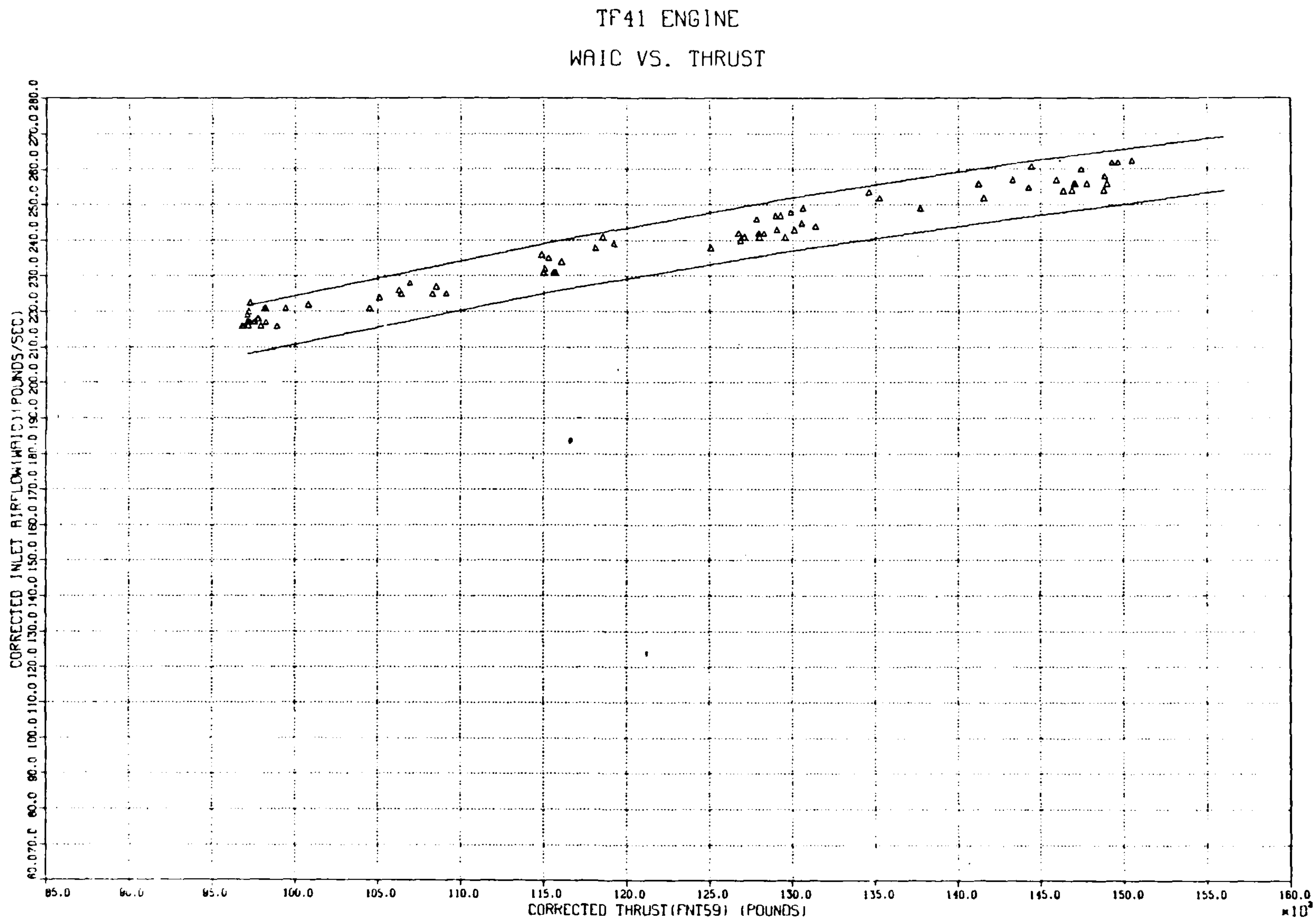


Figure 13 WAIC vs. Thrust

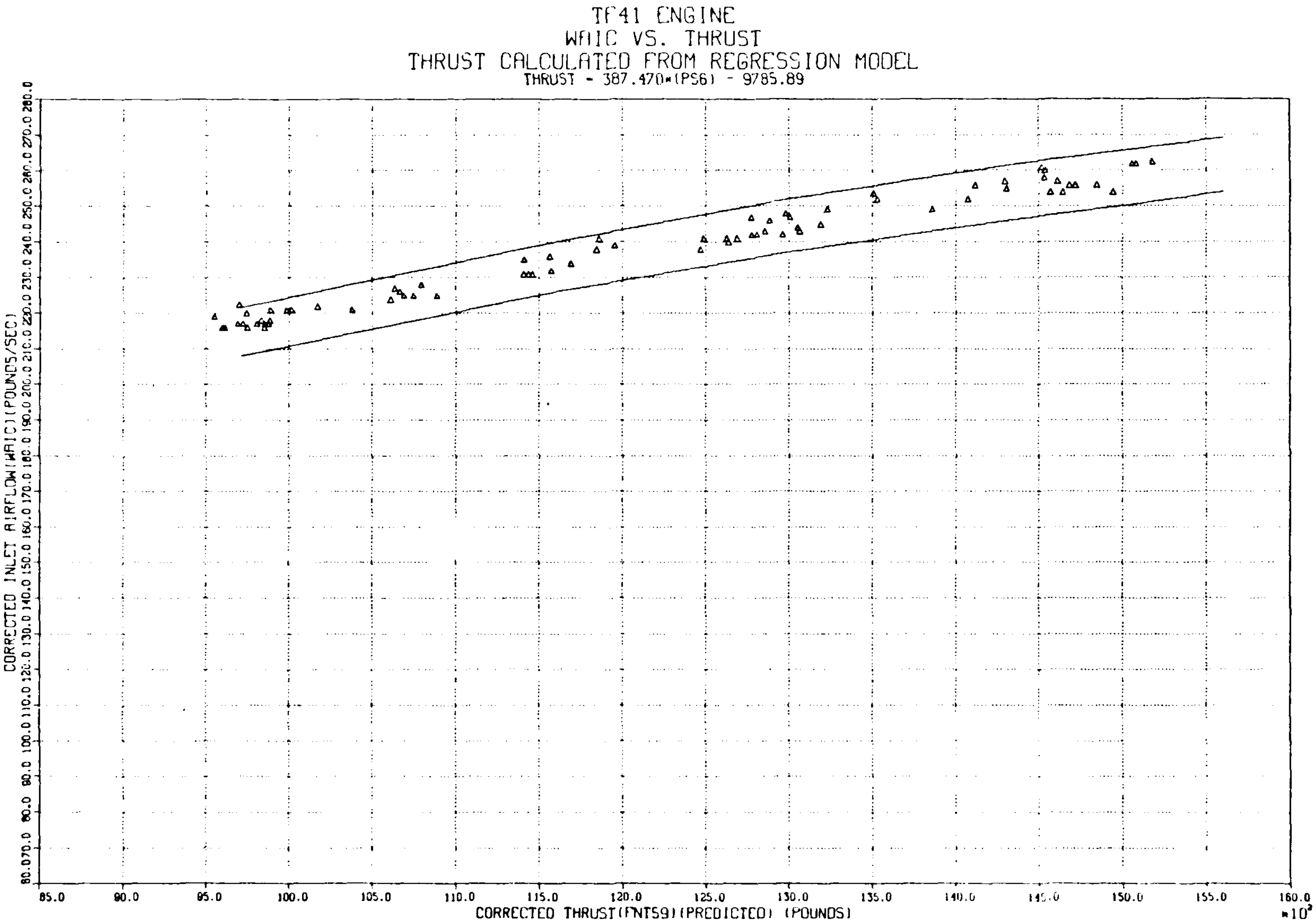


Figure 14 WAIC vs. Predicted Thrust

TF41 ENGINE

NLC VS. THRUST

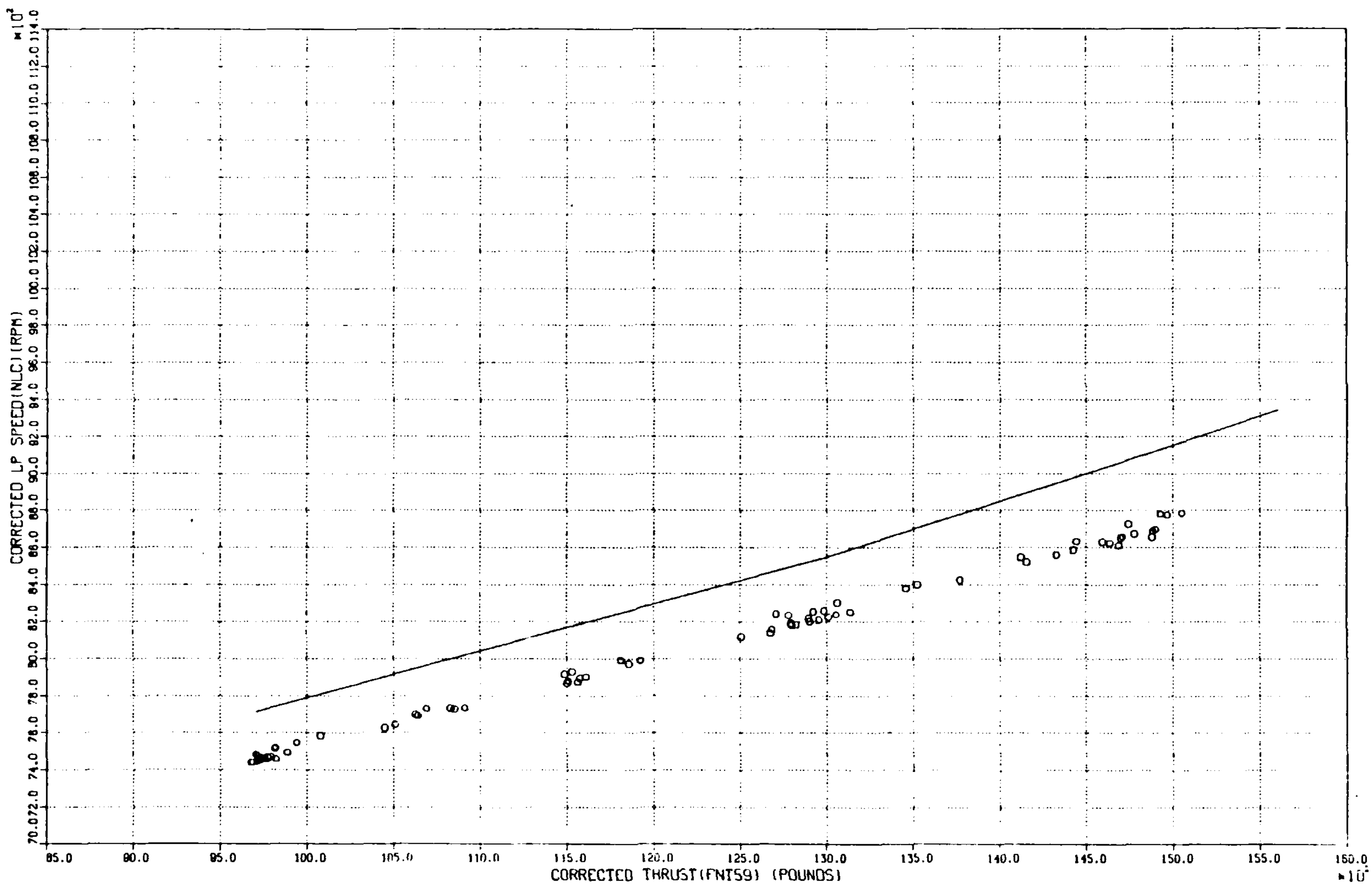


Figure 15 NLC vs. Thrust

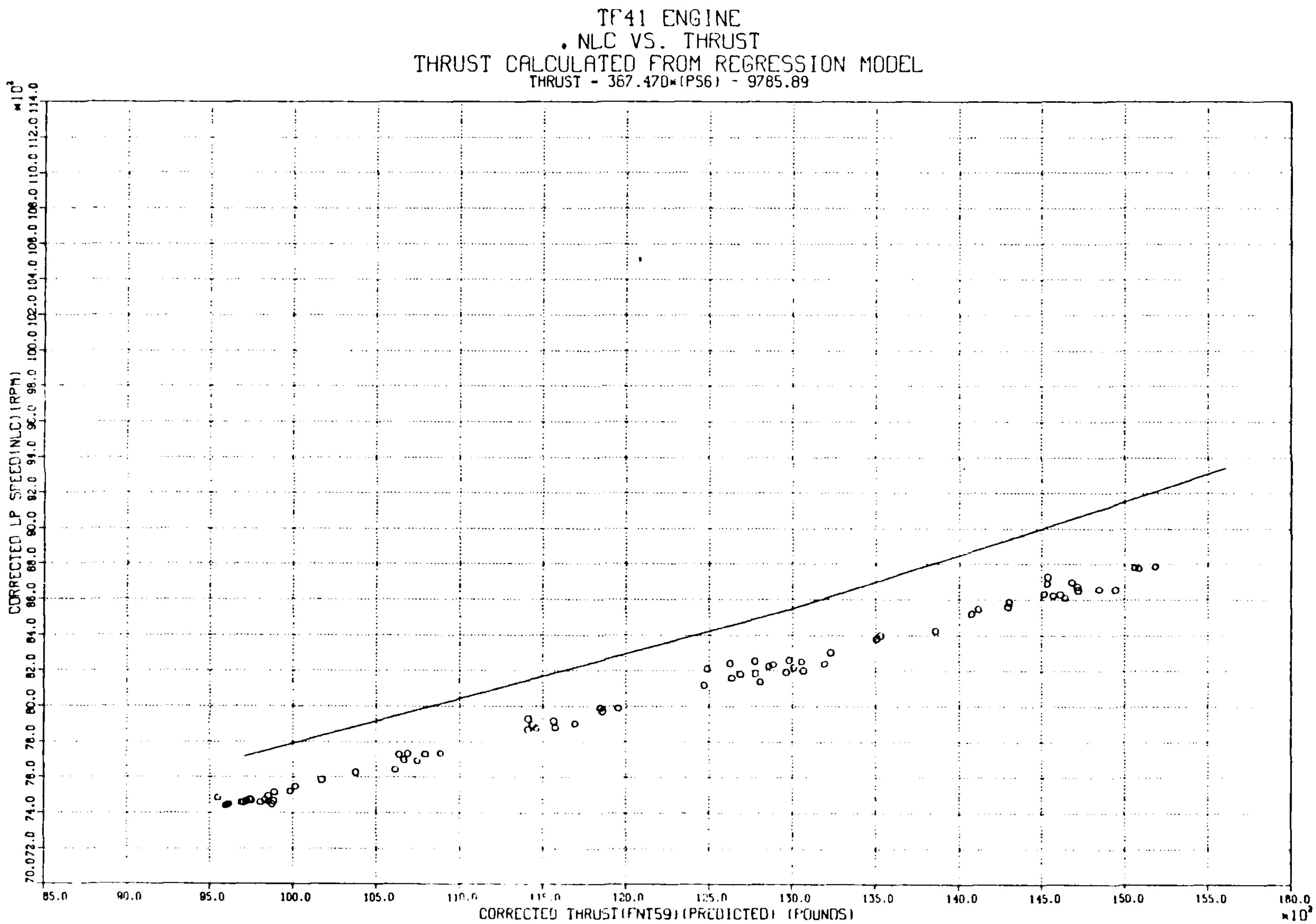


Figure 16 NLC vs. Predicted Thrust

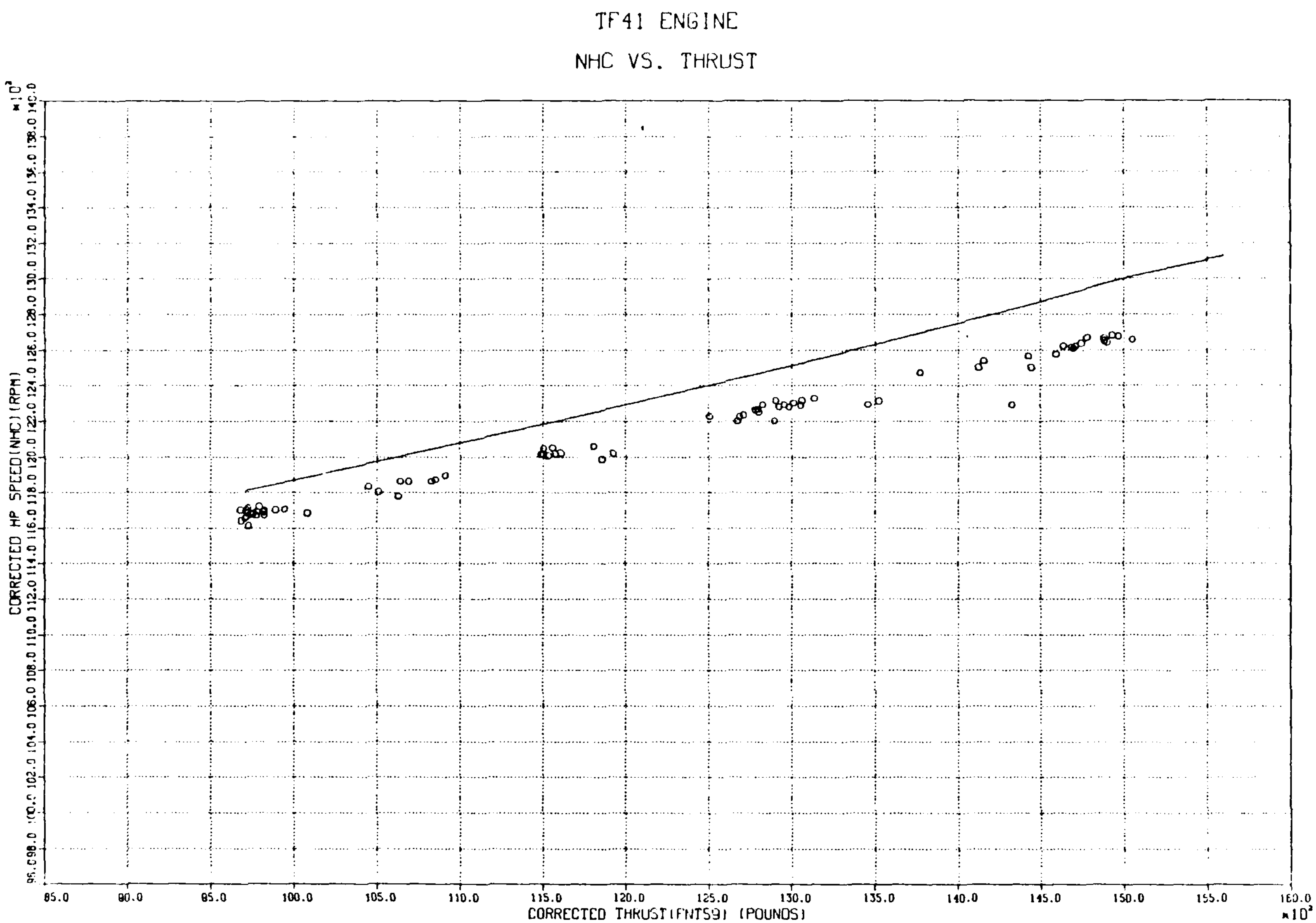


Figure 17 NHC vs. Thrust

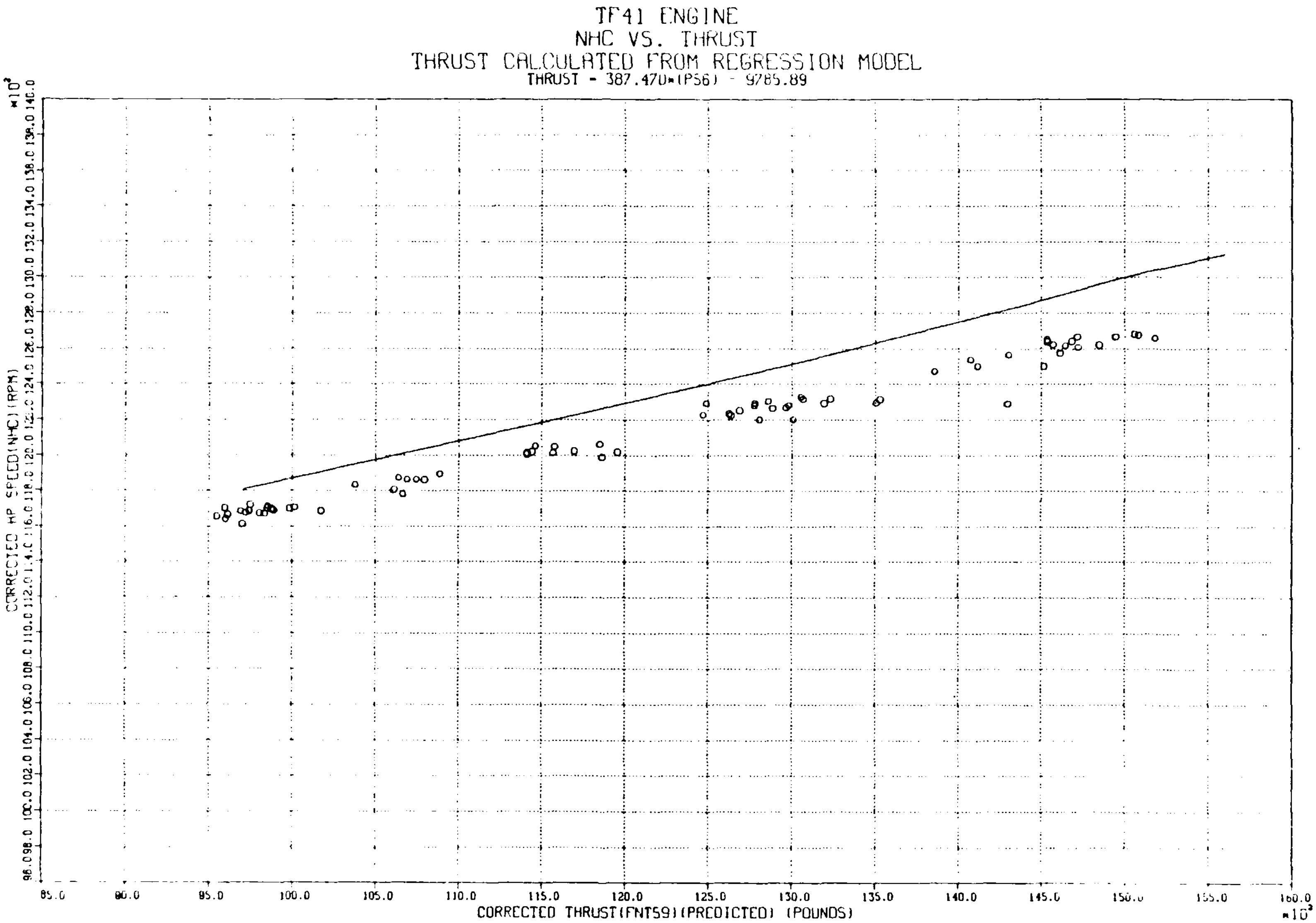


Figure 18 NHC vs. Predicted Thrust

IV. CONCLUSIONS

It is concluded that uninstalled thrust can be measured indirectly for the TF41 engine by connecting an instrumented tailpipe and measuring tailpipe static pressure. The accuracy associated with this procedure is obviously a strong function of the accuracy of the pressure measurement. For the purpose of the evaluation procedure from which these data were produced, it was found to be within acceptable limits.

The implications of this result are considered significant. Adoption of this technique, or some derivative of it, could save money and provide additional scheduling flexibility at the rework facilities. Additionally, and perhaps more significantly, implementation at the intermediate levels of maintenance could enhance flight safety by providing those levels with an additional diagnostic tool. Further, expanding the applicability of the technique could prove fruitful. For example, implementation of a trim-to-thrust technique for applicable engines could provide considerable cost savings and further enhance flight safety and operational readiness. While this was not part of our effort, in studies conducted by the USAF and NASA it was estimated that using a trim-to-thrust technique could result in savings of twelve million dollars

annually (in 1979 dollars) for the USAF F-4/J79 fleet and ten million dollars annually (in 1981 dollars) for the USAF T-38/J85 fleet, based on reductions in operating temperatures and the resulting reductions in fuel consumption, hot section parts and labor [Ref. 4].

V. RECOMMENDATIONS

Based on the results and conclusions of this study, the following recommendations are offered.

1. This technique, or a derivative, should be implemented by the depot and intermediate levels of maintenance for the TF41 engine in order to reduce cost, improve scheduling flexibility, and enhance flight safety.
2. An accuracy versus cost trade-off study should be conducted to determine an optimum instrumentation package for measuring tailpipe static pressure, keeping in mind that portability and low cost must be balanced against acceptable accuracy.
3. Similar studies should be conducted for other engines where thrust is used as the independent variable.
4. As suggested by Reference 4, further study of a trim-to-thrust technique and its implications should be conducted.

APPENDIX A

VARIATION OF THRUST WITH STATIC PRESSURE

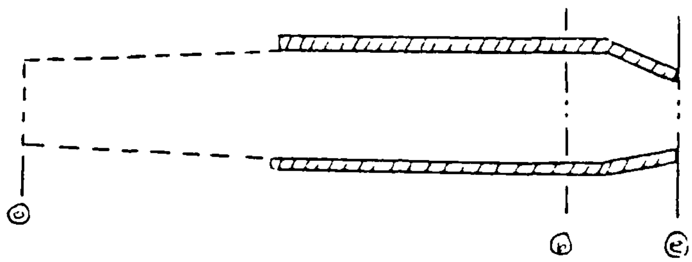


Figure A1 Schematic of Typical Engine

Thrust can be shown to vary directly with tailpipe static pressure based on a momentum analysis of the gas flow, but only after a series of simplifying assumptions are made. Consider the following:

For one-dimensional flow, the net propulsive thrust is defined as follows [Refs. 5 and 6]:

$$F \equiv \dot{m}_e V_e - \dot{m}_o V_o + A_e(p_e - p_o) = \rho_e V_e^{\,2} A_e - \rho_o V_o^{\,2} A_o + A_e(p_e - p_o)$$

See Figure A1. For an ideal gas, this relationship can be modified since

$$p = \rho RT; \; V = Ma; \; a = \sqrt{\gamma RT}$$

$$\rho V^2 = \frac{p}{RT} M^2 a^2 = \frac{p}{RT} M^2 \gamma RT = pM^2 \gamma$$

```
 605  FORMAT(1X,'PS6 MEAN = ',F10.2)
C
C**** CALCULATE LINEAR CORRLEATION COFFICIENT******
      S1 = 0.0
      S2 = 0.0
      S3 = 0.0
      S4 = 0.0
      S5 = 0.0
      S6 = 0.0
      S7 = 0.0
      DO 420 I = 1,Z
         S1 = S1 + X3(I)*Y3(I)
         S2 = S2 + X3(I)
         S3 = S3 + Y3(I)
         S4 = S4 + X3(I)**2
         S5 = S5 + Y3(I)**2
  420 CONTINUE
      S6 = S2**2
      S7 = S3**2
      R = (S1-(S2*S3)/FLOAT(Z))/(SQRT(S4-S6/FLOAT(Z))
     &      *SQRT(S5-S7/FLOAT(Z)))
C****CALCULATE THE COEFFICIENT OF DETERMINATION******
      RR = (S1-(S2*S3)/Z)**2/((S4-S6/Z)*(S5-S7/Z))
C****CALCULATE THE CONFIDENCE INTERVAL FOR THE SLOPE OF THE MODEL*****
      SA2 = SQRT(SS/(S4-S6/FLOAT(Z)))
      LCSLOP = A(2)-1.993*SA2
      UCSLOP = A(2)+1.993*SA2
      C = 1
 49   IF(C.EQ.2)GO TO 50
C***CALCULATE THE 95% PREDICTION INTERVAL FOR YNEXT**************
      DO 421 I=1,Z
         SSYN(I) = SS*(1.+1./FLOAT(Z)+((X3(I)-MX3)**2)/(S4-S6/FLOAT(Z)))
         SYN(I) = SQRT(SSYN(I))
         ASYN(I) = 1.993*SYN(I)
         UPLYN(I) = YBAR(I)+1.993*SYN(I)
         LPLYN(I) = YBAR(I)-1.993*SYN(I)
 421  CONTINUE
         WRITE(6,600)((X3(I),ASYN(I)),I=1,Z)
C
C     *** OUTPUT *****
C
      WRITE(6,610)IER
      WRITE(6,620)A
      WRITE(6,630)S
      WRITE(6,640)SS
      WRITE(6,645)SIGMA
      WRITE(6,655)R
      WRITE(6,656)RR
```

```
810   CONTINUE
      SAYBAR = 0.0
      DO 800 I=1,Z
         AYBAR(I)= Y3(I) - YBAR(I)
         SAYBAR = SAYBAR + AYBAR(I)
         IF((AYBAR(I).GT.0.0).AND.(AYBAR(I).LT.67.))O(1)=O(1)+1.
         IF((AYBAR(I).GE.67.).AND.(AYBAR(I).LT.134.))O(2)=O(2)+1.
         IF(AYBAR(I).GE.134.)O(3)=O(3)+1.
         IF((AYBAR(I).LE.0.0).AND.(AYBAR(I).GE.-67.))O(4)=O(4)+1.
         IF((AYBAR(I).LT.-67.).AND.(AYBAR(I).GE.-134.))O(5)=O(5)+1.
         IF(AYBAR(I).LT.-134.)O(6)=O(6)+1.
800   CONTINUE
      CHI = 0.0
      CHISQ = 0.0
      DO 910 I=1,6
         IF((I.EQ.1).OR.(I.EQ.4))E=13.
         IF((I.EQ.2).OR.(I.EQ.5))E=10.
         IF((I.EQ.3).OR.(I.EQ.6))E=10.
         CHI = (O(I)-E)**2/E
         CHISQ = CHI+CHISQ
910   CONTINUE
      WRITE(6,665)CHISQ
665   FORMAT(1X,'CHISQUARED =  ',F10.2)
      WRITE(6,666)(O(I),I=1,6)
666   FORMAT(1X,6F10.2)
      WRITE(6,667)SAYBAR
667   FORMAT(1X,F10.2)
C*****************************************************
C**** CALCULATE THE CONFIDENCE INTERVAL FOR THE MEAN CURVE******
      DO 700 I=1,Z
         SQSUM = SQSUM+X3(I)
         SUMSQ = SUMSQ+X3(I)**2
700   CONTINUE
      MX3 = SQSUM/FLOAT(Z)
      SQSUM = SQSUM**2
      DO 710 I=1,Z
         SSYBAR(I) = SS*(1./FLOAT(Z)+((X3(I)-MX3)**2/(SUMSQ-(SQSUM/
     $FLOAT(Z)))))
         SYBAR(I)=SQRT(SSYBAR(I))
710   CONTINUE
      DO 400 I=1,Z
        MYBAR(I) = YBAR(I) + 1.993*SYBAR(I)
400   CONTINUE
      DO 410 I=1,Z
        MYBAR(I) = YBAR(I)-(1.993*SYBAR(I))
410   CONTINUE
      WRITE(6,600)((X3(I),SYBAR(I)),I=1,Z)
      WRITE (6,605)MX3
```

```
      DO 1150 I = 46,53
         X3(I) = X(I+3)
         Y3(I) = Y(I+3)
 1150 CONTINUE
      DO 1160 I = 54,61
         X3(I) = X(I+4)
         Y3(I) = Y(I+4)
 1160 CONTINUE
      DO 1170 I = 62,67
         X3(I) = X(I+5)
         Y3(I) = Y(I+5)
 1170 CONTINUE
      ZZ = Z-1
      DO 1100 J = 1,ZZ
         L = J
         JJ = J + 1
         DO 1110 I = JJ,Z
            IF(X3(L).LT.X3(I))GO TO 1110
            L = I
 1110    CONTINUE
         T = X3(L)
         U = Y3(L)
         X3(L) = X3(J)
         Y3(L) = Y3(J)
         X3(J) = T
         Y3(J) = U
 1100 CONTINUE
C     ** DEBUG AID***
      WRITE(6,600)((X3(I),Y3(I)),I=1,Z)                                 TF400820
 600  FORMAT(1X,8F10.2)                                                 TF400830
C
C     *** CALCULATE COEFFICIENTS ******
C
      CALL IFLSQ(F,X3,Y3,Z,A,N,WK,IER)
C     *** CALCULATE THE SUM OF THE SQUARES OF THE DIFFERANCES ******
      S = 0.0
      DO 900 I = 1,Z
         YBAR(I) = A(1) + A(2)*(X3(I)-X0)
         S1 = (Y3(I)-YBAR(I))**2
         S = S + S1
 900  CONTINUE
C     *** CALCULATE THE ERROR VARIANCE ******
C
      SS = S/(FLOAT(Z)-FLOAT(N))
      SIGMA = SQRT(SS)
C****** PERFORM CHISQUARED TEST FOR GOODNESS OF FIT *******
       DO 810 I=1,6
          O(I)= 0.0
```

```
      KVPS6=.9991434+6.805E-5*W-1.7261E-6*W**2+2.1877E-8*W**3-1.2357E-10TF400490
     1*W**4+2.5516E-13*W**5                                             TF400500
      CPPS6=1.003923-6.76411E-5*DAT(5,J)                                TF400510
      X1(L,J) = (DAT(9,J)*KVPS6*CPPS6/DELTA)                            TF400520
C
C       (FG/FN) F/DELTA                                                 TF400660
C                                                                       TF400670
      CPFN=1.00708-1.2332E-4*DAT(5,J)+1.41685E-8*DAT(5,J)**2            TF400680
      KVFN=1.000316+9.738E-6*W+1.3439E-8*W**2                           TF400690
C     DAT(11,J)=DAT(10,J)*KVFN*CPFN/DELTA                               TF400700
C     DAT(12,J)=DAT(11,J)-248.25+.0414892*DAT(11,J)                     TF400710
      Y1(L,J)=DAT(12,J)                                                 TF400710
C     Y1(L,J) = (DAT(12,J)*1.00251)                                     TF400720
200   CONTINUE                                                          TF400810
      GO TO 10
 20   CONTINUE
 300  DO 310 I = 1,9
         DO 320 J = 1,8
            IF(J.EQ.1) X(I) = X1(I,J)
            IF(J.EQ.2) X(I+9) = X1(I,J)
            IF(J.EQ.3)X( I+18)=X1(I,J)
            IF(J.EQ.4)X( I+27)=X1(I,J)
            IF(J.EQ.5)X( I+36)=X1(I,J)
            IF(J.EQ.6)X( I+45)=X1(I,J)
            IF(J.EQ.7)X( I+54)=X1(I,J)
            IF(J.EQ.8)X( I+63)=X1(I,J)
            IF(J.EQ.1)Y( I)=Y1(I,J)
            IF(J.EQ.2)Y( I+9)=Y1(I,J)
            IF(J.EQ.3)Y( I+18)=Y1(I,J)
            IF(J.EQ.4)Y( I+27)=Y1(I,J)
            IF(J.EQ.5)Y( I+36)=Y1(I,J)
            IF(J.EQ.6)Y( I+45)=Y1(I,J)
            IF(J.EQ.7)Y( I+54)=Y1(I,J)
            IF(J.EQ.8)Y( I+63)=Y1(I,J)
 320     CONTINUE
 310  CONTINUE
      DO 1120 I = 1,13
         X3(I) = X(I)
         Y3(I) = Y(I)
 1120 CONTINUE
      DO 1130 I = 14,37
         X3(I) = X(I+1)
         Y3(I) = Y(I+1)
 1130 CONTINUE
      DO 1140 I = 38,45
         X3(I) = X(I+2)
         Y3(I) = Y(I+2)
 1140 CONTINUE
```

APPENDIX C

PROGRAM TO PERFORM A LINEAR REGRESSION
AND CORRELATION ANALYSIS

```
C        ************************************************
C        *     PROGRAM TO PERFORM A LINEAR REGRESSION     *
C        *          AND CORRELATION ANALYSIS.             *
C        ************************************************
C     ***** DECLARATION OF VARIABLES *****
      INTEGER Z,N,IER,I,J,L,B,NENG,M(50,2),H,ZZ,JJ,C
      REAL     X(72),Y(72),X1(9,8),Y1(9,8),DAT(50,8),W,ASYN(67),
     &         KVPS6,CPPS6,DELTA,DP,CPFN,KVFN,S,SS,S1,XO,THETA,RTHTA,
     &         WK(10),YBAR(67),A(2),S2,S3,S4,T,U,X3(67),Y3(67),SIGMA,F,
     &         S5,S6,S7,R,KVN,CHI,CHISQ,SUMSQ,SQSUM,MX3,SYBAR(67),
     &         SSYBAR(67),AYBAR(67),SAYBAR,D(6),RR,SSYN(67),SYN(67),
     &         UPLYN(67),LPLYN(67),MYBAR(67),SA2,LCSLOP,UCSLOP,
     &         PKRAY(500),ABSYN(67)
      EXTERNAL F
C        ** SET INITIAL CONDITIONS *****
      NENG = 9
      Z = 67
      N = 2
      XO = 0.0
      DO 1 I = 1,72
         X(I) = 0.0
         Y(I) = 0.0
    1 CONTINUE
      DO 2 I = 1,9
         DO 3 J =1,8
            X1(I,J) = 0.0
            Y1(I,J) = 0.0
    3    CONTINUE
    2 CONTINUE
      L = 0
   10 IF(L.EQ.NENG)GO TO 20
      L = L+1
C                                                                       TF400290
C     READ DATA FROM FILE                                               TF400300
C                                                                       TF400310
      READ(5,500)(M(I,1),M(I,2),(DAT(I,J),J=1,8),I=1,50)                TF400340
C                                                                       TF400360
C     CALC CORRECTED DATA FROM PRIMARY MEASUREMENTS                     TF400370
C                                                                       TF400380
      DO 200 J=1,8                                                      TF400390
      DELTA=DAT(4,J)/29.92                                              TF400410
      THETA=(DAT(5,J)+459.8)/519.0                                      TF400420
      RTHTA=SQRT(THETA)                                                 TF400430
      DP=DAT(2,J)                                                       TF400440
      W=-4.815+1.2438*DP-.0206*DP**2+.000376*DP**3                      TF400450
C                                                                       TF400460
C        PS6/DELTA                                                      TF400470
C                                                                       TF400480
```

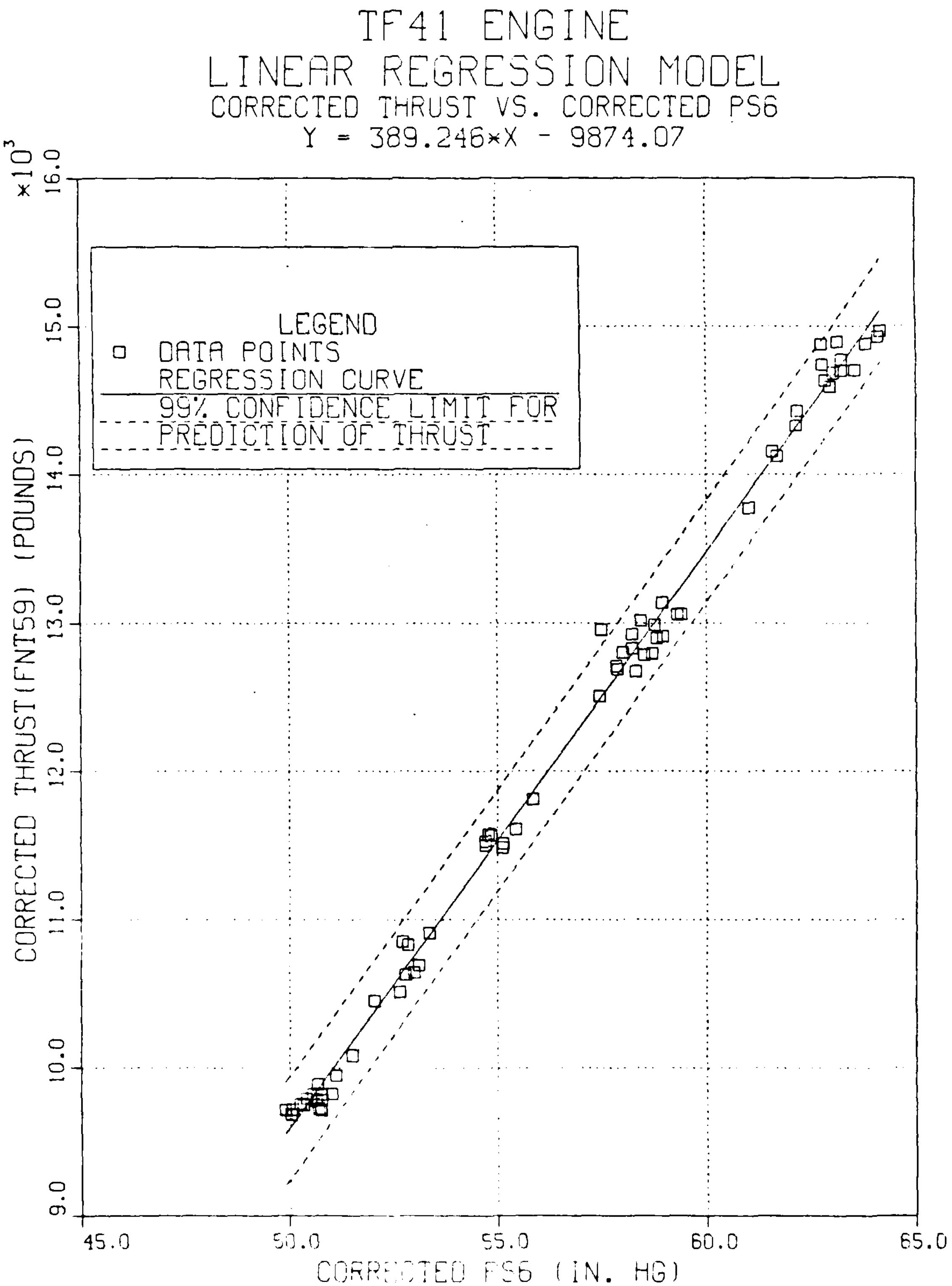


Figure B3 Thrust vs. ps6 (99% Conf.)

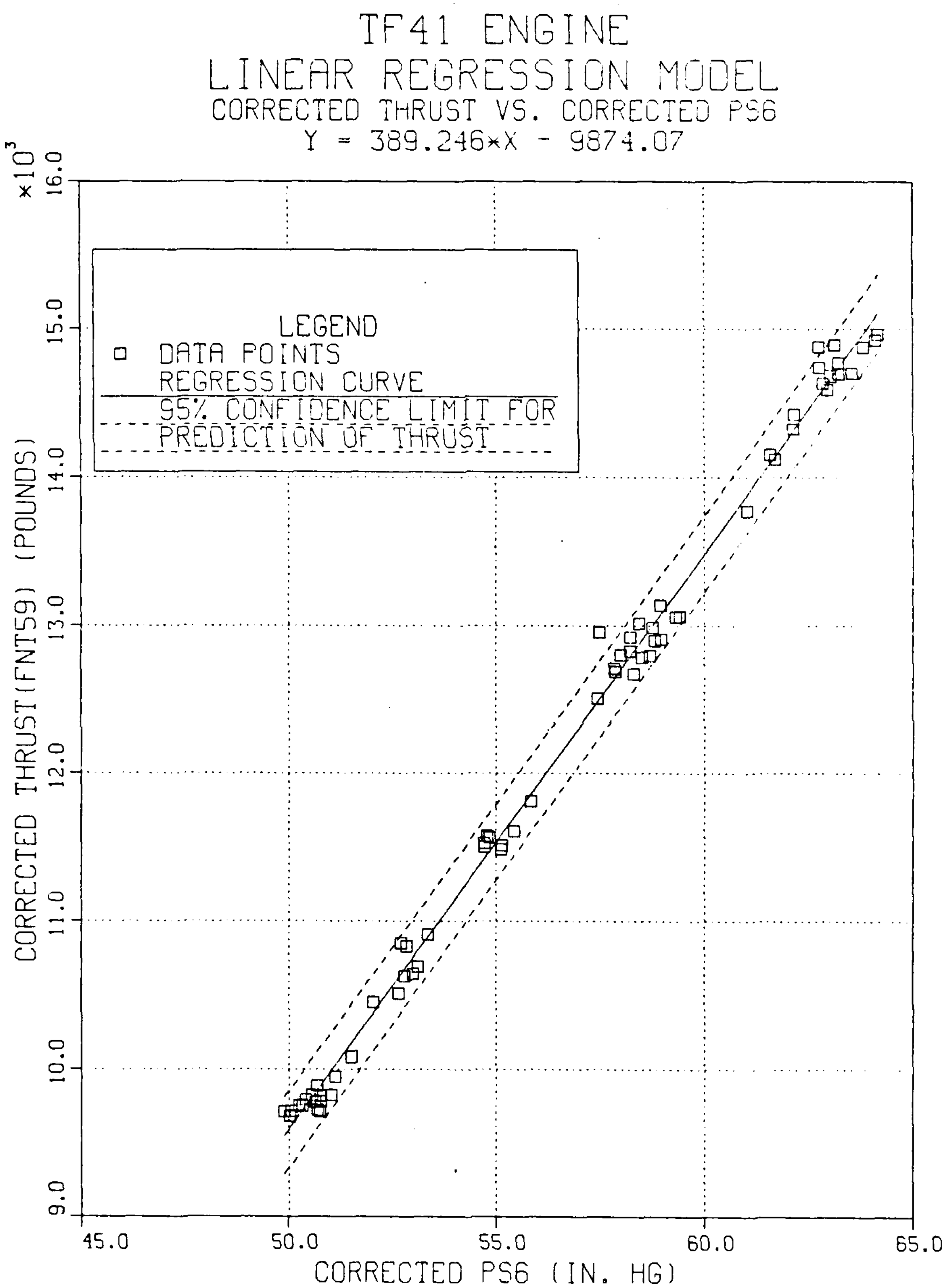


Figure B2 Thrust vs. ps6

The standardized random variable t was used for the test, where

$$t = \frac{r}{\sqrt{\frac{1-r^2}{n-2}}}$$

This variable is t-distributed with n-2 degrees of freedom. At the 95% Confidence Level and with 73 degrees of freedom, the hypothesis that rho equalled zero was rejected since t=126.2 which is greater than the significant value of t=1.993 (see Appendix 5 of Ref. 9).

A confidence interval was established about the value of rho (the population correlation coefficient) based on the calculated value of r (the sample correlation coefficient). At the 95% Confidence Level

0.9951.LE.rho.LE.0.9993

See Chapter 8-5 of Ref. 9 for details.

And finally, confidence intervals were placed about the model's mean line, both at the 95% and 99% levels, to help clarify the model's ability to correctly predict thrust. See Figures B2 and B3.

TABLE B1

REGION	EXPECTED VALUE	OBSERVED VALUE	CHI-SQUARE
1 (0-67)	15.2775	15	0.005
2 (67-134)	11.55	13	0.182
3 (134+)	10.6725	8	0.669
4 (0-(-67))	15.2775	12	0.703
5 ((-67)-(-134))	11.55	16	1.715
6 ((-134)-)	10.6725	11	0.010
			3.284

As a further quantitative measure of the degree of association between the two variables, the sample correlation coefficient was calculated. This parameter is defined as follows:

$$r = \frac{\sum_n (x_i-\bar{x})(y_i-\bar{y})}{\left\{\sum_n (x_i-\bar{x})^2\right\}^{1/2}\left\{\sum_n (y_i-\bar{y})^2\right\}^{1/2}}$$

The value of r was found to be close to unity (r=0.9976).

The validity of the sample correlation coefficient was tested by hypothesizing that the population correlation coefficient was equal to zero. That is,

H_o: rho.EQ.0

H_a: rho.NE.0

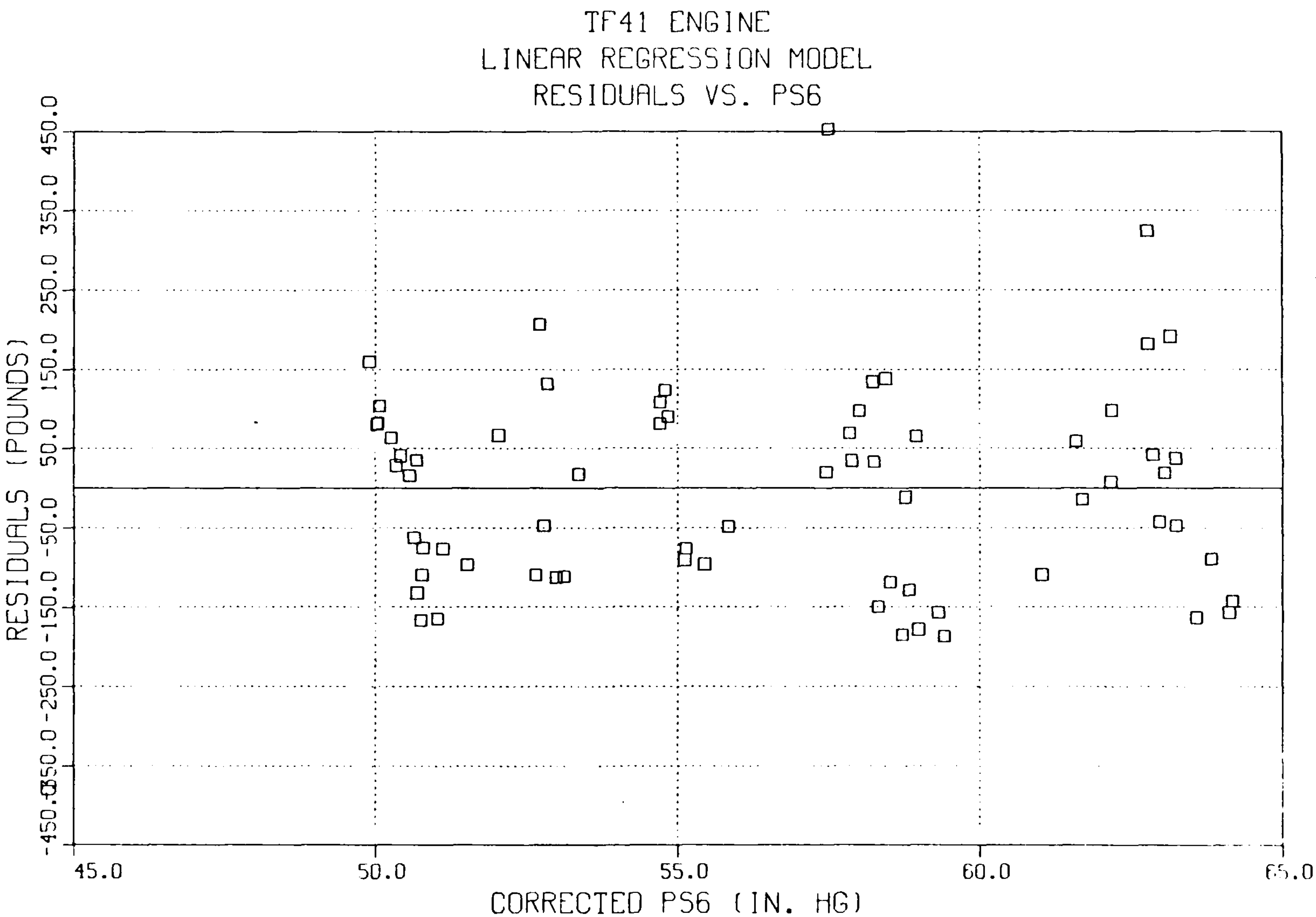


Figure B1 Residuals vs. ps6

mean and constant variance. And thirdly, the errors are assumed to be normally distributed.

Several techniques were employed in testing the validity of these assumptions. The first of these, and perhaps the most compelling intuitively, was an examination of a plot of the residuals (the difference between the observed and fitted values) versus the independent variable (see Figure B1). It can be readily seen that, with the exception of two outliers, all the data are displayed in a horizontal band with an average value of zero and a reasonably constant variance.

The assumption of normality in the distribution of errors was proven to be reasonable by use of the Chi-square statistical test [Ref. 9]. The residuals were divided into six regions as shown in Table B1. Two degrees of freedom were utilized in estimating the frequency classes and the standard deviation from the mean, leaving four degrees of freedom for the test. Employing the Normal Distribution table in Appendix 3 of Reference 9, the expected values of the frequency of errors in each region were determined. The results are shown in Table B1.

At the 95% Confidence Level, Chi-square equals 9.49 for four degrees of freedom and since the calculated value is less than the significant value, the hypothesis that the errors are, in fact, normally distributed was accepted.

APPENDIX B

CURVE FITTING BY LEAST SQUARES

The method of least squares was employed to evaluate the relationship between tailpipe static pressure and thrust. Since inspection of the initial scatter diagram of the data indicated that thrust varied linearly, or nearly so, with ps6, and since the theoretical argument presented in Appendix A indicates that such a relationship is physically plausible, a model of the form $Y=a_1+a_2*X+e$ was chosen.

Calculation of the estimated coefficients a_1 and a_2 was accomplished by a standard technique wherein

$$a_2 = \frac{\sum_n (x_i-\bar{x})(y_i-\bar{y})}{\sum_n (x_i-\bar{x})^2} = \frac{\sum_n x_i y_i - \frac{1}{n}\sum_n x_i \sum_n y_i}{\sum_n x_i^2 - \frac{1}{n}(\sum_n x_i)^2}$$

$$a_1 = \bar{y} - a_2\bar{x}$$

See Reference 8 and the FORTRAN program in Appendix C for details.

Some assumptions are implicitly made when employing such a model. First, the values of the independent parameter are assumed to be measured without error; that is, all errors are assumed to be in the dependent variable. Secondly, the error term, e, is assumed to be a random variable with zero

For choked flow, M_6 and gamma will not vary significantly and p_e will be directly proportional to p_6, ie, $p_e = k*p_6$. Corrected thrust will then vary only with p_6 as follows:

$$F/\delta = A_e[kp_6/\delta(\gamma_e+1)-p_{SD}] = f(p_6/\delta)$$

The difference between this ideal analysis and the actual flow condition is, in effect, the crux of the problem. If the difference is consistent, it can be accounted for by an empirical constant. If not, another parameter (or parameters) must be introduced in order to explain this difference.

For the purposes of this project, the only assumption made in the above that might introduce a significant deviation from ideal behavior is the assumption of one-dimensionality. In a turbofan engine, conditions in the tailpipe are apt to be "very non-uniform" [Ref. 7] because of flow mixing, depending on tailpipe length, mixer design, by pass ratio, etc. For this reason, accurate measurement of total (stagnation) pressure is very difficult and use of a more common parameter, such as Engine Pressure Ratio (EPR), for the independent parameter in the project was rejected. The errors associated with tailpipe static pressure were felt to be 1) smaller and 2) more consistent (and, therefore, more predictable).

$$F = p_e \gamma_e M_e^2 A_e - p_o r_o M_o^2 \; A_o - A_e(p_e - p_o)$$

For the static case, $M_o = 0$:

$$F = p_e \gamma_e M_e^2 A_e + A_e(p_e - p_o)$$

For choked flow, $M_e = 1$:

$$F = p_e \gamma_e A_e + p_e A_e - p_o A_e \; = A_e[p_e(\gamma_e + 1) - p_o]$$

Correcting for deviations from standard day conditions yields

$$F/\delta = A_e[p_e/\delta \;\; (\gamma_e + 1) - p_{SD}]$$

Thus, for a given atmospheric pressure, thrust varies only with exit pressure. Ignoring losses in the nozzle, it can be shown [Ref. 5] that

$$\frac{p_n}{p_t} = f(M_n, \gamma_n)$$

$$\frac{p_e}{p_6} = \left(\frac{p_e}{p_{te}}\right)\left(\frac{p_{te}}{p_{t6}}\right)\left(\frac{p_{t6}}{p_6}\right)$$

$$\frac{p_e}{p_6} = f(M_6, \gamma_6, \gamma_e)$$

```
      WRITE(6,657)LCSLOP,UCSLOP
C     WRITE(6,660)
C     ******* SET PLOT AREA **************
 51   CALL CCMPRS
      CALL BLOWUP(.88)
C51   CALL TEK618
C     CALL HWROT('AUTO')
      CALL PAGE(8.5,11.0)
C     CALL PAGE(6,8.5)
C     CALL PAGE(22,15)
      CALL NOBRDR
C     CALL PHYSOR(1.5,1.5)
C     CALL PHYSOR(1.0,1.0)
      CALL AREA2D(6,7.5)
C     CALL AREA2D(15.0,16.0)
C     CALL AREA2D(17.1,10.7)
      CALL XNAME('CORRECTED PS6 (IN. HG)$',100)
      CALL YNAME('CORRECTED THRUST(FNT59) (POUNDS)$',100)
      CALL HEADIN('TF41 ENGINES$',100,1.5,4)
      CALL HEADIN('LINEAR REGRESSION MODELS$',100,1.5,4)
      CALL HEADIN('CORRECTED THRUST VS. CORRECTED PS6$',100,1.0,4)
      CALL HEADIN('Y = 389.246*X - 9874.07$',100,1.0,4)
      CALL GRAF(45.,5.,65.,9000.,1000.,16000.)
      IF(C.EQ.2)GO TO 56
C     CALL MESSAG('FIGURE 1. THURST VS. PS6$',100,0.0,-1.0)
      CALL MESSAG('FIGURE B2. THRUST VS. PS6$',100,0.0,-1.0)
 57   CALL BLREC(.1,5.4,3.5,1.6,.01)
      MAXLIN=LINEST(PKRAY,500,100)
      CALL LINES('DATA POINTS$',PKRAY,1)
      CALL LINES('REGRESSION CURVES$',PKRAY,2)
      IF(C.EQ.2)GO TO 52
      CALL LINES('95% CONFIDENCE LIMIT FOR$',PKRAY,3)
 53   CALL LINES('PREDICTION OF THRUST$',PKRAY,4)
      CALL DOT
      CALL GRID(1,1)
      CALL RESET('ALL')
      CALL LEGLIN
      CALL CURVE(X3,Y3,Z,-1)
      CALL CURVE(X3,YBAR,Z,0)
      CALL RASPLN(0.25)
      CALL DASH
      CALL CURVE(X3,UPLYN,Z,0)
      CALL CURVE(X3,LPLYN,Z,0)
      CALL LEGEND(PKRAY,4,.15,5.5)
      CALL ENDPL(0)
      IF(C.EQ.2)GO TO 54
      C = 2
      GO TO 49
```

```
C***CALCULATE THE 99% PREDICTION INTERVAL FOR YNEXT**************
 50   DO 422 I=1,Z
         SSYN(I) = SS*(1.+1./FLOAT(Z)+((X3(I)-MX3)**2)/(S4-S6/FLOAT(Z)))
         SYN(I) = SQRT(SSYN(I))
         ABSYN(I) = 2.643*SYN(I)
         UPLYN(I) = YBAR(I)+2.643*SYN(I)
         LPLYN(I) = YBAR(I)-2.643*SYN(I)
 422  CONTINUE
         WRITE(6,600)((X3(I),ABSYN(I)),I=1,Z)
      GO TO 51
 52   CALL LINES('99% CONFIDENCE LIMIT FOR$',PKRAY,3)
      GO TO 53
C56   CALL MESSAG('FIGURE 1. THURST VS. PS6$',100,0.0,-1.0)
 56   CALL MESSAG('FIGURE B3. THURST VS. PS6$',100,0.0,-1.0)
      GO TO 57
C     ******* SET PLOT AREA **************
  54  CALL CCMPRS
      CALL BLOWUP(.9)
C 54  CALL TEK618
C     CALL HWROT('AUTO')
      CALL PAGE(11.0,8.5)
C     CALL PAGE(8.5,11)
      CALL NOBRDR
C     CALL PHYSOR(1.0,1.0)
      CALL AREA2D(8.5,5.0)
      CALL XNAME('CORRECTED PS6 (IN. HG)$',100)
      CALL YNAME('RESIDUALS (POUNDS)$',100)
      CALL HEADIN('TF41 ENGINES',100,1.0,3)
      CALL HEADIN('LINEAR REGRESSION MODEL$',100,1.0,3)
      CALL HEADIN('RESIDUALS VS. PS6$',100,1.0,3)
      CALL GRAF(45.,5.,65.,-450,100,450)
      CALL RLVEC(45,0,65,0,0000)
C     CALL MESSAG('FIGURE 2. RESIDUALS VS. PS6$',100,0.0,-1.0)
      CALL MESSAG('FIGURE B1. RESIDUALS VS. PS6$',100,0.0,-1.0)
      CALL DOT
      CALL GRID(1,1)
      CALL RESET('ALL')
      CALL CURVE(X3,AYBAR,Z,-1)
      CALL ENDPL(0)
      CALL DONEPL
      STOP
C
 500  FORMAT(2A4,8F8.2)
 610  FORMAT('1','IER = ',I3)
 620  FORMAT(1X,'COEFFICENTS FOR THE POLYNOMIAL CURVE FIT ARE: '/1X,
     &        'A1 = ',E12.6/1X,'A2 = ',E12.6//)
 630  FORMAT(1X,'THE SUM OF THE SQUARES OF THE DIFFERENCES IS: '/1X,
     &        'S = ',E12.6//)
```

TF400350

```
640   FORMAT(1X,'THE RESIDUAL ERROR VARIANCE IS: '/1X,'SS = ',E12.6//)
645   FORMAT(1X,'THE STANDARD DEVIATION IS: '/1X,'SIGMA = ',E12.6//)
655   FORMAT(1X,'THE LINEAR CORRELATION COFFICIENT IS:'/1X,
     &        'R = ',E12.6//)
656   FORMAT(1X,'THE COEFFICIENT OF DETERMINATION IS:'/1X,
     &        'RR = ',E12.6//)
657   FORMAT(1X,'THE CONFIDENCE INTERVAL FOR THE SLOPE OF THE MODEL '
     &        'IS:'/1X,E12.6,' TO ',E12.6//)
      END                                                          TF401380
      REAL FUNCTION F(K,X)
      INTEGER K
      REAL X,RK
      RK = K
      F = X**(RK-1.0)
      RETURN
      END
```

APPENDIX D

DATA

The following is a portion of the data received from the Naval Air Rework Facility, Jacksonville, Florida. The corrected thrust (FNT(59)) was measured in a calibrated test cell and utilized as is. It should be noted that engine S/N 142618, a "correlation engine", had been used at the start of our project to verify the proper calibration of the test cell. Tailpipe static pressure was measured by utilizing a "slave" tailpipe instrumented with a series of pressure transducers. See Figure D1 and D2.

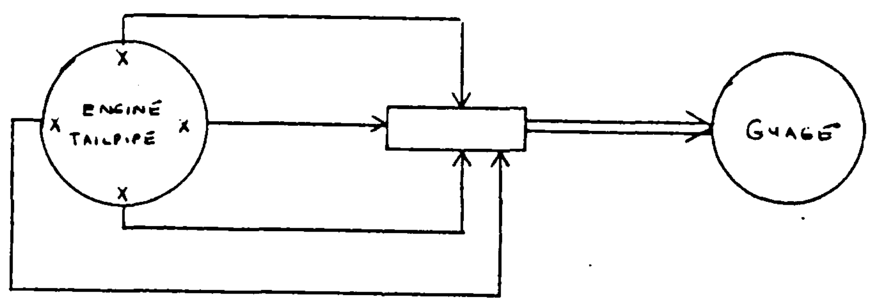
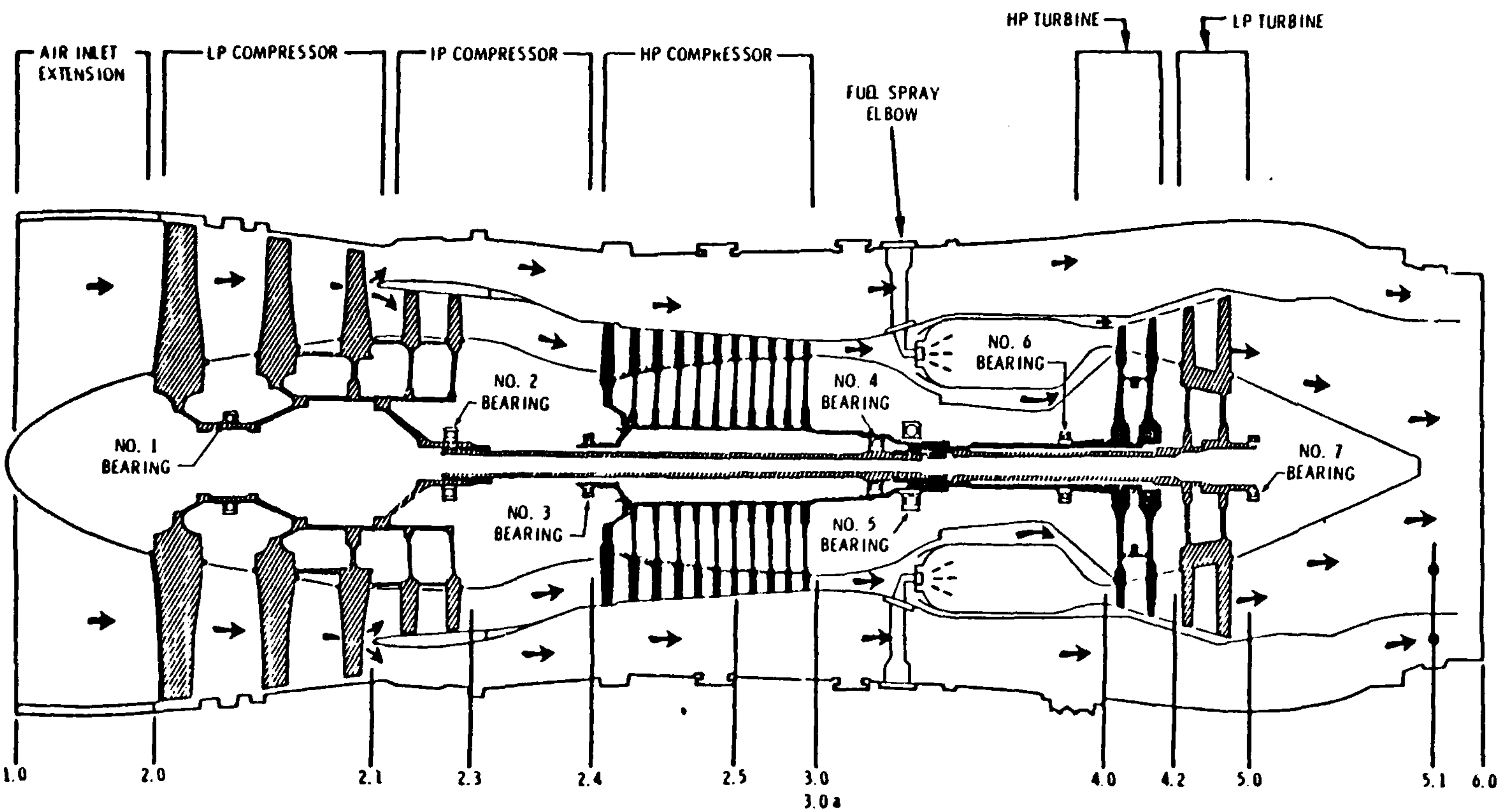


Figure D1 Instrumentation Setup

The result (ps6) is an average value. Corrected tailpipe static pressure (ps6c) resulted from applying the same correction factor utilized in correcting other pressure values in reference 3. See Appendix C.



1.0 ENGINE INLET
2.0 LP COMPRESSOR INLET
2.1 BYPASS DUCT INLET
2.3 IP COMPRESSOR OUTLET
2.4 HP COMPRESSOR INLET
2.5 7TH-STAGE BLEED OUTLET
3.0 HP COMPRESSOR OUTLET
3.0 a FUEL HEATER BLEED OUTLET (TF41-A-2, -2A)
4.0 HP TURBINE INLET
4.2 LP TURBINE INLET
5.0 LP TURBINE OUTLET
5.1 MEASURED GAS PRESSURE AND TEMPERATURE STATION
6.0 ENGINE OUTLET

Figure D2 TF41 Engine Station Schematic

ENGINE S/N	FNT(59) (lbf)	PS6 (in-Hg)	PS6C (in-Hg)
141481	9717	50.4	50.05
	11575	55.1	54.79
	12802	58.3	58.01
	14895	63.4	63.14
	9685	50.2	50.05
	10828	53.0	52.85
	12687	58.0	57.87
	14696	63.3	63.24
141525	9678	50.4	50.02
	11563	55.2	54.84
	12828	58.6	58.24
	14775	63.6	63.23
	9792	50.8	50.42
	10450	52.4	52.04
	12506	57.8	57.44
	14633	63.2	62.85
142634	9710	50.2	49.90
	11530	55.0	54.71
	12926	58.5	58.23
	14742	63.0	62.77
141954	9755	50.4	50.27
	11503	54.8	54.71
	13013	58.5	58.44
	14156	61.6	61.58
	9750	50.3	50.34
	10852	52.6	52.72
	12711	57.7	57.84
	14425	62.0	62.17

141427	9724	50.6	50.69
	11510	55.0	55.13
	12906	58.8	58.98
	13772	60.8	61.03
	9712	50.81	50.75
	10641	53.06	52.99
	12796	58.67	58.71
	14706	63.52	63.57
141972	9822	50.4	51.02
	11487	54.4	55.11
	13063	58.6	59.41
	14925	63.2	64.11
	9817	50.50	50.78
	10692	52.81	53.12
	12783	58.13	58.51
	14963	63.65	64.17
141440	9943	49.98	51.11
	11812	54.57	55.84
	12987	57.41	58.76
	14125	60.21	61.69
	10081	50.00	51.51
	10627	51.20	52.79
	12897	57.00	58.83
	14328	60.20	62.16
142633	9822	49.9	50.56
	13137	58.1	58.95
	14878	62.6	63.82
	9889	50.3	50.68
	10912	52.9	53.36
	12957	57.0	57.49
	14685	62.4	63.04

141257	9778	50.4	50.77
	11610	55.0	55.44
	13056	58.8	59.31
	14880	62.2	62.76
	9773	50.6	50.63
	10511	52.6	52.65
	12675	58.2	58.31
	14592	62.8	62.96
142618	9722.6	50.4	50.4
	11925.0	56.0	56.11
	13526.5	60.0	60.18
	15047.1	64.2	64.43
	9729.0	50.3	50.3
	11858.4	55.8	55.87
	13459.3	60.0	60.11
	14441.8	62.6	62.72

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